Red Hat Enterprise Linux 6 Performance Tuning Guide

Optimizing subsystem throughput in Red Hat Enterprise Linux 6
Edition 4.0

Red Hat Subject Matter Experts

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Abstract

The Performance Tuning Guide describes how to optimize the performance of a system running Red Hat Enterprise Linux 6. It also documents performance-related upgrades in Red Hat Enterprise Linux 6. While this guide contains procedures that are field-tested and proven, Red Hat recommends that you properly test all planned configurations in a testing environment before applying it to a production environment. You should also back up all your data and pre-tuning configurations.

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Preface

1. Document Conventions

This manual uses several conventions to highlight certain words and phrases and draw attention to specific pieces of information.

In PDF and paper editions, this manual uses typefaces drawn from the Liberation Fonts set. The Liberation Fonts set is also used in HTML editions if the set is installed on your system. If not, alternative but equivalent typefaces are displayed. Note: Red Hat Enterprise Linux 5 and later include the Liberation Fonts set by default.

1.1. Typographic Conventions

Four typographic conventions are used to call attention to specific words and phrases. These conventions, and the circumstances they apply to, are as follows.

`Mono-spaced Bold`

Used to highlight system input, including shell commands, file names and paths. Also used to highlight keys and key combinations. For example:

> To see the contents of the file **`my_next_bestselling_novel`** in your current working directory, enter the **`cat my_next_bestselling_novel`** command at the shell prompt and press **`Enter`** to execute the command.

The above includes a file name, a shell command and a key, all presented in mono-spaced bold and all distinguishable thanks to context.

Key combinations can be distinguished from an individual key by the plus sign that connects each part of a key combination. For example:

> Press **`Enter`** to execute the command.
>
> Press **`Ctrl`**+**`Alt`**+**`F2`** to switch to a virtual terminal.

The first example highlights a particular key to press. The second example highlights a key combination: a set of three keys pressed simultaneously.

If source code is discussed, class names, methods, functions, variable names and returned values mentioned within a paragraph will be presented as above, in **`mono-spaced bold`**. For example:

> File-related classes include **`filesystem`** for file systems, **`file`** for files, and **`dir`** for directories. Each class has its own associated set of permissions.

Proportional Bold

This denotes words or phrases encountered on a system, including application names; dialog-box text; labeled buttons; check-box and radio-button labels; menu titles and submenu titles. For example:

> Choose **System** → **Preferences** → **Mouse** from the main menu bar to launch **Mouse Preferences**. In the **`Buttons`** tab, select the **`Left-handed mouse`** check box and click **`Close`** to switch the primary mouse button from the left to the right (making the mouse suitable for use in the left hand).
>
> To insert a special character into a **gedit** file, choose **Applications** → **Accessories** →

Character Map from the main menu bar. Next, choose **Search** → **Find...** from the **Character Map** menu bar, type the name of the character in the **Search** field and click **Next**. The character you sought will be highlighted in the **Character Table**. Double-click this highlighted character to place it in the **Text to copy** field and then click the **Copy** button. Now switch back to your document and choose **Edit** → **Paste** from the **gedit** menu bar.

The above text includes application names; system-wide menu names and items; application-specific menu names; and buttons and text found within a GUI interface, all presented in proportional bold and all distinguishable by context.

Mono-spaced Bold Italic or ***Proportional Bold Italic***

Whether mono-spaced bold or proportional bold, the addition of italics indicates replaceable or variable text. Italics denotes text you do not input literally or displayed text that changes depending on circumstance. For example:

To connect to a remote machine using ssh, type **ssh *username*@*domain.name*** at a shell prompt. If the remote machine is **example.com** and your username on that machine is john, type **ssh john@example.com**.

The **mount -o remount *file-system*** command remounts the named file system. For example, to remount the **/home** file system, the command is **mount -o remount /home**.

To see the version of a currently installed package, use the **rpm -q *package*** command. It will return a result as follows: ***package-version-release***.

Note the words in bold italics above: username, domain.name, file-system, package, version and release. Each word is a placeholder, either for text you enter when issuing a command or for text displayed by the system.

Aside from standard usage for presenting the title of a work, italics denotes the first use of a new and important term. For example:

Publican is a *DocBook* publishing system.

1.2. Pull-quote Conventions

Terminal output and source code listings are set off visually from the surrounding text.

Output sent to a terminal is set in **mono-spaced roman** and presented thus:

```
books        Desktop   documentation  drafts  mss    photos   stuff  svn
books_tests  Desktop1  downloads      images  notes  scripts  svgs
```

Source-code listings are also set in **mono-spaced roman** but add syntax highlighting as follows:

```
static int kvm_vm_ioctl_deassign_device(struct kvm *kvm,
                 struct kvm_assigned_pci_dev *assigned_dev)
{
         int r = 0;
         struct kvm_assigned_dev_kernel *match;

         mutex_lock(&kvm->lock);

         match = kvm_find_assigned_dev(&kvm->arch.assigned_dev_head,
                                       assigned_dev->assigned_dev_id);
         if (!match) {
                 printk(KERN_INFO "%s: device hasn't been assigned before, "
                   "so cannot be deassigned\n", __func__);
                 r = -EINVAL;
                 goto out;
         }

         kvm_deassign_device(kvm, match);

         kvm_free_assigned_device(kvm, match);

out:
         mutex_unlock(&kvm->lock);
         return r;
}
```

1.3. Notes and Warnings

Finally, we use three visual styles to draw attention to information that might otherwise be overlooked.

Note

Notes are tips, shortcuts or alternative approaches to the task at hand. Ignoring a note should have no negative consequences, but you might miss out on a trick that makes your life easier.

Important

Important boxes detail things that are easily missed: configuration changes that only apply to the current session, or services that need restarting before an update will apply. Ignoring a box labeled “Important” will not cause data loss but may cause irritation and frustration.

Warning

Warnings should not be ignored. Ignoring warnings will most likely cause data loss.

2. Getting Help and Giving Feedback

2.1. Do You Need Help?

If you experience difficulty with a procedure described in this documentation, visit the Red Hat Customer

Portal at http://access.redhat.com. Through the customer portal, you can:

- search or browse through a knowledgebase of technical support articles about Red Hat products.
- submit a support case to Red Hat Global Support Services (GSS).
- access other product documentation.

Red Hat also hosts a large number of electronic mailing lists for discussion of Red Hat software and technology. You can find a list of publicly available mailing lists at https://www.redhat.com/mailman/listinfo. Click on the name of any mailing list to subscribe to that list or to access the list archives.

2.2. We Need Feedback!

If you find a typographical error in this manual, or if you have thought of a way to make this manual better, we would love to hear from you! Please submit a report in Bugzilla: http://bugzilla.redhat.com/ against the product **Red Hat Enterprise Linux 6.**

When submitting a bug report, be sure to mention the manual's identifier: *doc-Performance_Tuning_Guide*

If you have a suggestion for improving the documentation, try to be as specific as possible when describing it. If you have found an error, please include the section number and some of the surrounding text so we can find it easily.

Chapter 1. Overview

The *Performance Tuning Guide* is a comprehensive reference on the configuration and optimization of Red Hat Enterprise Linux. While this release also contains information on Red Hat Enterprise Linux 5 performance capabilities, all instructions supplied herein are specific to Red Hat Enterprise Linux 6.

1.1. How to read this book

This book is divided into chapters discussing specific subsystems in Red Hat Enterprise Linux. The *Performance Tuning Guide* focuses on three major themes per subsystem:

Features

Each subsystem chapter describes performance features unique to (or implemented differently in) Red Hat Enterprise Linux 6. These chapters also discuss Red Hat Enterprise Linux 6 updates that significantly improved the performance of specific subsystems over Red Hat Enterprise Linux 5.

Analysis

The book also enumerates performance indicators for each specific subsystem. Typical values for these indicators are described in the context of specific services, helping you understand their significance in real-world, production systems.

In addition, the *Performance Tuning Guide* also shows different ways of retrieving performance data (that is, profiling) for a subsystem. Note that some of the profiling tools showcased here are documented elsewhere with more detail.

Configuration

Perhaps the most important information in this book are instructions on how to adjust the performance of a specific subsystem in Red Hat Enterprise Linux 6. The *Performance Tuning Guide* explains how to fine-tune a Red Hat Enterprise Linux 6 subsystem for specific services.

Keep in mind that tweaking a specific subsystem's performance may affect the performance of another, sometimes adversely. The default configuration of Red Hat Enterprise Linux 6 is optimal for *most* services running under *moderate* loads.

The procedures enumerated in the *Performance Tuning Guide* were tested extensively by Red Hat engineers in both lab and field. However, Red Hat recommends that you properly test all planned configurations in a secure testing environment before applying it to your production servers. You should also back up all data and configuration information before you start tuning your system.

1.1.1. Audience

This book is suitable for two types of readers:

System/Business Analyst

This book enumerates and explains Red Hat Enterprise Linux 6 performance features at a high level, providing enough information on how subsystems perform for specific workloads (both by default and when optimized). The level of detail used in describing Red Hat Enterprise Linux 6 performance features helps potential customers and sales engineers understand the suitability of this platform in providing resource-intensive services at an acceptable level.

The *Performance Tuning Guide* also provides links to more detailed documentation on each

feature whenever possible. At that detail level, readers can understand these performance features enough to form a high-level strategy in deploying and optimizing Red Hat Enterprise Linux 6. This allows readers to both develop *and* evaluate infrastructure proposals.

This feature-focused level of documentation is suitable for readers with a high-level understanding of Linux subsystems and enterprise-level networks.

System Administrator

The procedures enumerated in this book are suitable for system administrators with RHCE [1] skill level (or its equivalent, that is, 3-5 years experience in deploying and managing Linux). The *Performance Tuning Guide* aims to provide as much detail as possible about the effects of each configuration; this means describing any performance trade-offs that may occur.

The underlying skill in performance tuning lies not in knowing how to analyze and tune a subsystem. Rather, a system administrator adept at performance tuning knows how to balance and optimize a Red Hat Enterprise Linux 6 system *for a specific purpose*. This means *also* knowing which trade-offs and performance penalties are acceptable when attempting to implement a configuration designed to boost a specific subsystem's performance.

1.2. Release overview

1.2.1. Summary of features

1.2.1.1. New features in Red Hat Enterprise Linux 6

Read this section for a brief overview of the performance-related changes included in Red Hat Enterprise Linux 6.

1.2.1.1.1. New in 6.5

- Updates to the kernel remove a bottleneck in memory management and improve performance by allowing I/O load to spread across multiple memory pools when the irq-table size is 1 GB or greater.
- The *cpupowerutils* package has been updated to include the **turbostat** and **x86_energy_perf_policy** tools. These tools are newly documented in Section 4.1.4, “ **turbostat**” and Section 4.1.3, “Hardware performance policy (**x86_energy_perf_policy**)”.
- CIFS now supports larger rsize options and asynchronous readpages, allowing for significant increases in throughput.
- GFS2 now provides an Orlov block allocator to increase the speed at which block allocation takes place.
- The ***virtual-hosts*** profile in **tuned** has been adjusted. The value for ***kernel.sched_migration_cost*** is now **5000000** nanoseconds (5 milliseconds) instead of the kernel default **500000** nanoseconds (0.5 milliseconds). This reduces contention at the run queue lock for large virtualization hosts.
- The ***latency-performance*** profile in **tuned** has been adjusted. The value for power management quality of service, **cpu_dma_latency** requirement, is now **1** instead of **0**.
- Several optimizations are now included in the kernel **copy_from_user()** and **copy_to_user()** functions, improving the performance of both.
- The perf tool has received a number of updates and enhancements, including:

- Perf can now use hardware counters provided by the System z CPU-measurement counter facility. There are four sets of hardware counters available: the basic counter set, the problem-state counter set, the crypto-activity counter set, and the extended counter set.
- A new command, **`perf trace`**, is now available. This enables **`strace`**-like behavior using **`perf`** infrastructure to allow additional targets to be traced. For further information, refer to Section 3.5.4, “Perf”.
- A script browser has been added to enable users to view all available scripts for the current perf data file.
- Several additional sample scripts are now available.

- Ext3 has been updated to reduce lock contention, thereby improving the performance of multi-threaded write operations.
- KSM has been updated to be aware of NUMA topology, allowing it to take NUMA locality into account while coalescing pages. This prevents performance drops related to pages being moved to a remote node. Red Hat recommends avoiding cross-node memory merging when KSM is in use.

  This update introduces a new tunable, **`/sys/kernel/mm/ksm/merge_nodes`**, to control this behavior. The default value (**`1`**) merges pages across different NUMA nodes. Set ***`merge_nodes`*** to **`0`** to merge pages only on the same node.
- **`hdparm`** has been updated with several new flags, including **`--fallocate`**, **`--offset`**, and **`-R`** (Write-Read-Verify enablement). Additionally, the **`--trim-sector-ranges`** and **`--trim-sector-ranges-stdin`** options replace the **`--trim-sectors`** option, allowing more than a single sector range to be specified. Refer to the man page for further information about these options.

1.2.2. Horizontal Scalability

Red Hat's efforts in improving the performance of Red Hat Enterprise Linux 6 focus on *scalability*. Performance-boosting features are evaluated primarily based on how they affect the platform's performance in different areas of the workload spectrum — that is, from the lonely web server to the server farm mainframe.

Focusing on scalability allows Red Hat Enterprise Linux to maintain its versatility for different types of workloads and purposes. At the same time, this means that as your business grows and your workload scales up, re-configuring your server environment is less prohibitive (in terms of cost and man-hours) and more intuitive.

Red Hat makes improvements to Red Hat Enterprise Linux for both *horizontal scalability* and *vertical scalability*; however, horizontal scalability is the more generally applicable use case. The idea behind horizontal scalability is to use multiple *standard computers* to distribute heavy workloads in order to improve performance and reliability.

In a typical server farm, these standard computers come in the form of 1U rack-mounted servers and blade servers. Each standard computer may be as small as a simple two-socket system, although some server farms use large systems with more sockets. Some enterprise-grade networks mix large and small systems; in such cases, the large systems are high performance servers (for example, database servers) and the small ones are dedicated application servers (for example, web or mail servers).

This type of scalability simplifies the growth of your IT infrastructure: a medium-sized business with an appropriate load might only need two pizza box servers to suit all their needs. As the business hires more people, expands its operations, increases its sales volumes and so forth, its IT requirements increase in both volume and complexity. Horizontal scalability allows IT to simply deploy additional machines with (mostly) identical configurations as their predecessors.

To summarize, horizontal scalability adds a layer of abstraction that simplifies system hardware administration. By developing the Red Hat Enterprise Linux platform to scale horizontally, increasing the

capacity and performance of IT services can be as simple as adding new, easily configured machines.

1.2.2.1. Parallel Computing

Users benefit from Red Hat Enterprise Linux's horizontal scalability not just because it simplifies system hardware administration; but also because horizontal scalability is a suitable development philosophy given the current trends in hardware advancement.

Consider this: most complex enterprise applications have thousands of tasks that must be performed simultaneously, with different coordination methods between tasks. While early computers had a single-core processor to juggle all these tasks, virtually all processors available today have multiple cores. Effectively, modern computers put multiple cores in a single socket, making even single-socket desktops or laptops multi-processor systems.

As of 2010, standard Intel and AMD processors were available with two to sixteen cores. Such processors are prevalent in pizza box or blade servers, which can now contain as many as 40 cores. These low-cost, high-performance systems bring large system capabilities and characteristics into the mainstream.

To achieve the best performance and utilization of a system, each core must be kept busy. This means that 32 separate tasks must be running to take advantage of a 32-core blade server. If a blade chassis contains ten of these 32-core blades, then the entire setup can process a minimum of 320 tasks simultaneously. If these tasks are part of a single job, they must be coordinated.

Red Hat Enterprise Linux was developed to adapt well to hardware development trends and ensure that businesses can fully benefit from them. Section 1.2.3, “Distributed Systems” explores the technologies that enable Red Hat Enterprise Linux's horizontal scalability in greater detail.

1.2.3. Distributed Systems

To fully realize horizontal scalability, Red Hat Enterprise Linux uses many components of *distributed computing*. The technologies that make up distributed computing are divided into three layers:

Communication

Horizontal scalability requires many tasks to be performed simultaneously (in parallel). As such, these tasks must have *interprocess communication* to coordinate their work. Further, a platform with horizontal scalability should be able to share tasks across multiple systems.

Storage

Storage via local disks is not sufficient in addressing the requirements of horizontal scalability. Some form of distributed or shared storage is needed, one with a layer of abstraction that allows a single storage volume's capacity to grow seamlessly with the addition of new storage hardware.

Management

The most important duty in distributed computing is the *management* layer. This management layer coordinates all software and hardware components, efficiently managing communication, storage, and the usage of shared resources.

The following sections describe the technologies within each layer in more detail.

1.2.3.1. Communication

The communication layer ensures the transport of data, and is composed of two parts:

- Hardware
- Software

The simplest (and fastest) way for multiple systems to communicate is through *shared memory*. This entails the usage of familiar memory read/write operations; shared memory has the high bandwidth, low latency, and low overhead of ordinary memory read/write operations.

Ethernet

The most common way of communicating between computers is over Ethernet. Today, *Gigabit Ethernet* (GbE) is provided by default on systems, and most servers include 2-4 ports of Gigabit Ethernet. GbE provides good bandwidth and latency. This is the foundation of most distributed systems in use today. Even when systems include faster network hardware, it is still common to use GbE for a dedicated management interface.

10GbE

Ten Gigabit Ethernet (10GbE) is rapidly growing in acceptance for high end and even mid-range servers. 10GbE provides ten times the bandwidth of GbE. One of its major advantages is with modern multi-core processors, where it restores the balance between communication and computing. You can compare a single core system using GbE to an eight core system using 10GbE. Used in this way, 10GbE is especially valuable for maintaining overall system performance and avoiding communication bottlenecks.

Unfortunately, 10GbE is expensive. While the cost of 10GbE NICs has come down, the price of interconnect (especially fibre optics) remains high, and 10GbE network switches are extremely expensive. We can expect these prices to decline over time, but 10GbE today is most heavily used in server room backbones and performance-critical applications.

Infiniband

Infiniband offers even higher performance than 10GbE. In addition to TCP/IP and UDP network connections used with Ethernet, Infiniband also supports shared memory communication. This allows Infiniband to work between systems via *remote direct memory access* (RDMA).

The use of RDMA allows Infiniband to move data directly between systems without the overhead of TCP/IP or socket connections. In turn, this reduces latency, which is critical to some applications.

Infiniband is most commonly used in *High Performance Technical Computing* (HPTC) applications which require high bandwidth, low latency and low overhead. Many supercomputing applications benefit from this, to the point that the best way to improve performance is by investing in Infiniband rather than faster processors or more memory.

RoCE

RDMA over Converged Ethernet (RoCE) implements Infiniband-style communications (including RDMA) over a 10GbE infrastructure. Given the cost improvements associated with the growing volume of 10GbE products, it is reasonable to expect wider usage of RDMA and RoCE in a wide range of systems and applications.

Each of these communication methods is fully-supported by Red Hat for use with Red Hat Enterprise Linux 6.

1.2.3.2. Storage

An environment that uses distributed computing uses multiple instances of shared storage. This can mean one of two things:

- Multiple systems storing data in a single location
- A storage unit (e.g. a volume) composed of multiple storage appliances

The most familiar example of storage is the local disk drive mounted on a system. This is appropriate for IT operations where all applications are hosted on one host, or even a small number of hosts. However, as the infrastructure scales to dozens or even hundreds of systems, managing as many local storage disks becomes difficult and complicated.

Distributed storage adds a layer to ease and automate storage hardware administration as the business scales. Having multiple systems share a handful of storage instances reduces the number of devices the administrator needs to manage.

Consolidating the storage capabilities of multiple storage appliances into one volume helps both users and administrators. This type of distributed storage provides a layer of abstraction to storage pools: users see a single unit of storage, which an administrator can easily grow by adding more hardware. Some technologies that enable distributed storage also provide added benefits, such as failover and multipathing.

NFS

Network File System (NFS) allows multiple servers or users to mount and use the same instance of remote storage via TCP or UDP. NFS is commonly used to hold data shared by multiple applications. It is also convenient for bulk storage of large amounts of data.

SAN

Storage Area Networks (SANs) use either Fibre Channel or iSCSI protocol to provide remote access to storage. Fibre Channel infrastructure (such as Fibre Channel host bus adapters, switches, and storage arrays) combines high performance, high bandwidth, and massive storage. SANs separate storage from processing, providing considerable flexibility in system design.

The other major advantage of SANs is that they provide a management environment for performing major storage hardware administrative tasks. These tasks include:

- Controlling access to storage
- Managing large amounts of data
- Provisioning systems
- Backing up and replicating data
- Taking snapshots
- Supporting system failover
- Ensuring data integrity
- Migrating data

GFS2

The Red Hat *Global File System 2* (GFS2) file system provides several specialized capabilities. The basic function of GFS2 is to provide a single file system, including concurrent read/write access, shared across multiple members of a cluster. This means that each member of the cluster sees exactly the same data "on disk" in the GFS2 filesystem.

GFS2 allows all systems to have concurrent access to the "disk". To maintain data integrity, GFS2 uses a *Distributed Lock Manager* (DLM), which only allows one system to write to a specific location at a time.

GFS2 is especially well-suited for failover applications that require high availability in storage.

For further information about GFS2, refer to the *Global File System 2*. For further information about storage in general, refer to the *Storage Administration Guide*. Both are available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

1.2.3.3. Converged Networks

Communication over the network is normally done through Ethernet, with storage traffic using a dedicated Fibre Channel SAN environment. It is common to have a dedicated network or serial link for system management, and perhaps even *heartbeat* [2]. As a result, a single server is typically on multiple networks.

Providing multiple connections on each server is expensive, bulky, and complex to manage. This gave rise to the need for a way to consolidate all connections into one. *Fibre Channel over Ethernet* (FCoE) and *Internet SCSI* (iSCSI) address this need.

FCoE

With FCoE, standard fibre channel commands and data packets are transported over a 10GbE physical infrastructure via a single *converged network adapter* (CNA). Standard TCP/IP ethernet traffic and fibre channel storage operations can be transported via the same link. FCoE uses one physical network interface card (and one cable) for multiple logical network/storage connections.

FCoE offers the following advantages:

Reduced number of connections

FCoE reduces the number of network connections to a server by half. You can still choose to have multiple connections for performance or availability; however, a single connection provides both storage and network connectivity. This is especially helpful for pizza box servers and blade servers, since they both have very limited space for components.

Lower cost

Reduced number of connections immediately means reduced number of cables, switches, and other networking equipment. Ethernet's history also features great economies of scale; the cost of networks drops dramatically as the number of devices in the market goes from millions to billions, as was seen in the decline in the price of 100Mb Ethernet and gigabit Ethernet devices.

Similarly, 10GbE will also become cheaper as more businesses adapt to its use. Also, as CNA hardware is integrated into a single chip, widespread use will also increase its volume in the market, which will result in a significant price drop over time.

iSCSI

Internet SCSI (iSCSI) is another type of converged network protocol; it is an alternative to FCoE. Like fibre channel, iSCSI provides block-level storage over a network. However, iSCSI does not provide a complete management environment. The main advantage of iSCSI over FCoE is that iSCSI provides much of the capability and flexibility of fibre channel, but at a lower cost.

[1] Red Hat Certified Engineer. For more information, refer to http://www.redhat.com/training/certifications/rhce/.

[2] *Heartbeat* is the exchange of messages between systems to ensure that each system is still functioning. If a system "loses

heartbeat" it is assumed to have failed and is shut down, with another system taking over for it.

Chapter 2. Red Hat Enterprise Linux 6 Performance Features

2.1. 64-Bit Support

Red Hat Enterprise Linux 6 supports 64-bit processors; these processors can theoretically use up to 16 *exabytes* of memory. As of general availability (GA), Red Hat Enterprise Linux 6.0 is tested and certified to support up to 8 TB of physical memory.

The size of memory supported by Red Hat Enterprise Linux 6 is expected to grow over several minor updates, as Red Hat continues to introduce and improve more features that enable the use of larger memory blocks. For current details, see http://www.redhat.com/resourcelibrary/articles/articles-red-hat-enterprise-linux-6-technology-capabilities-and-limits. Example improvements (as of Red Hat Enterprise Linux 6.0 GA) are:

- Huge pages and transparent huge pages
- Non-Uniform Memory Access improvements

These improvements are outlined in greater detail in the sections that follow.

Huge pages and transparent huge pages

The implementation of *huge pages* in Red Hat Enterprise Linux 6 allows the system to manage memory use efficiently across different memory workloads. Huge pages dynamically utilize 2 MB pages compared to the standard 4 KB page size, allowing applications to scale well while processing gigabytes and even terabytes of memory.

Huge pages are difficult to manually create, manage, and use. To address this, Red Hat Enterprise 6 also features the use of *transparent huge pages* (THP). THP automatically manages many of the complexities involved in the use of huge pages.

For more information on huge pages and THP, refer to Section 5.2, “Huge Pages and Transparent Huge Pages”.

NUMA improvements

Many new systems now support *Non-Uniform Memory Access* (NUMA). NUMA simplifies the design and creation of hardware for large systems; however, it also adds a layer of complexity to application development. For example, NUMA implements both local and remote memory, where remote memory can take several times longer to access than local memory. This feature has performance implications for operating systems and applications, and should be configured carefully.

Red Hat Enterprise Linux 6 is better optimized for NUMA use, thanks to several additional features that help manage users and applications on NUMA systems. These features include CPU affinity, CPU pinning (cpusets), numactl and control groups, which allow a process (affinity) or application (pinning) to "bind" to a specific CPU or set of CPUs.

For more information about NUMA support in Red Hat Enterprise Linux 6, refer to Section 4.1.1, “CPU and NUMA Topology”.

2.2. Ticket Spinlocks

A key part of any system design is ensuring that one process does not alter memory used by another process. Uncontrolled data change in memory can result in data corruption and system crashes. To prevent this, the operating system allows a process to lock a piece of memory, perform an operation,

then unlock or "free" the memory.

One common implementation of memory locking is through *spin locks*, which allow a process to keep checking to see if a lock is available and take the lock as soon as it becomes available. If there are multiple processes competing for the same lock, the first one to request the lock after it has been freed gets it. When all processes have the same access to memory, this approach is "fair" and works quite well.

Unfortunately, on a NUMA system, not all processes have equal access to the locks. Processes on the same NUMA node as the lock have an unfair advantage in obtaining the lock. Processes on remote NUMA nodes experience lock starvation and degraded performance.

To address this, Red Hat Enterprise Linux implemented *ticket spinlocks*. This feature adds a reservation queue mechanism to the lock, allowing *all* processes to take a lock in the order that they requested it. This eliminates timing problems and unfair advantages in lock requests.

While a ticket spinlock has slightly more overhead than an ordinary spinlock, it scales better and provides better performance on NUMA systems.

2.3. Dynamic List Structure

The operating system requires a set of information on each processor in the system. In Red Hat Enterprise Linux 5, this set of information was allocated to a fixed-size array in memory. Information on each individual processor was obtained by indexing into this array. This method was fast, easy, and straightforward for systems that contained relatively few processors.

However, as the number of processors for a system grows, this method produces significant overhead. Because the fixed-size array in memory is a single, shared resource, it can become a bottleneck as more processors attempt to access it at the same time.

To address this, Red Hat Enterprise Linux 6 uses a *dynamic list structure* for processor information. This allows the array used for processor information to be allocated dynamically: if there are only eight processors in the system, then only eight entries are created in the list. If there are 2048 processors, then 2048 entries are created as well.

A dynamic list structure allows more fine-grained locking. For example, if information needs to be updated at the same time for processors 6, 72, 183, 657, 931 and 1546, this can be done with greater parallelism. Situations like this obviously occur much more frequently on large, high-performance systems than on small systems.

2.4. Tickless Kernel

In previous versions of Red Hat Enterprise Linux, the kernel used a timer-based mechanism that continuously produced a system interrupt. During each interrupt, the system *polled*; that is, it checked to see if there was work to be done.

Depending on the setting, this system interrupt or *timer tick* could occur several hundred or several thousand times per second. This happened every second, regardless of the system's workload. On a lightly loaded system, this impacts *power consumption* by preventing the processor from effectively using sleep states. The system uses the least power when it is in a sleep state.

The most power-efficient way for a system to operate is to do work as quickly as possible, go into the deepest sleep state possible, and sleep as long as possible. To implement this, Red Hat Enterprise Linux 6 uses a *tickless kernel*. With this, the interrupt timer has been removed from the idle loop, transforming Red Hat Enterprise Linux 6 into a completely interrupt-driven environment.

The tickless kernel allows the system to go into deep sleep states during idle times, and respond quickly when there is work to be done.

For further information, refer to the *Power Management Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

2.5. Control Groups

Red Hat Enterprise Linux provides many useful options for performance tuning. Large systems, scaling to hundreds of processors, can be tuned to deliver superb performance. But tuning these systems requires considerable expertise and a well-defined workload. When large systems were expensive and few in number, it was acceptable to give them special treatment. Now that these systems are mainstream, more effective tools are needed.

To further complicate things, more powerful systems are being used now for service consolidation. Workloads that may have been running on four to eight older servers are now placed into a single server. And as discussed earlier in Section 1.2.2.1, “Parallel Computing”, many mid-range systems nowadays contain more cores than yesterday's high-performance machines.

Many modern applications are designed for parallel processing, using multiple threads or processes to improve performance. However, few applications can make effective use of more than eight threads. Thus, multiple applications typically need to be installed on a 32-CPU system to maximize capacity.

Consider the situation: small, inexpensive mainstream systems are now at parity with the performance of yesterday's expensive, high-performance machines. Cheaper high-performance machines gave system architects the ability to consolidate more services to fewer machines.

However, some resources (such as I/O and network communications) are shared, and do not grow as fast as CPU count. As such, a system housing multiple applications can experience degraded overall performance when one application hogs too much of a single resource.

To address this, Red Hat Enterprise Linux 6 now supports *control groups* (cgroups). Cgroups allow administrators to allocate resources to specific tasks as needed. This means, for example, being able to allocate 80% of four CPUs, 60GB of memory, and 40% of disk I/O to a database application. A web application running on the same system could be given two CPUs, 2GB of memory, and 50% of available network bandwidth.

As a result, both database and web applications deliver good performance, as the system prevents both from excessively consuming system resources. In addition, many aspects of cgroups are *self-tuning*, allowing the system to respond accordingly to changes in workload.

A cgroup has two major components:

- A list of tasks assigned to the cgroup
- Resources allocated to those tasks

Tasks assigned to the cgroup run *within* the cgroup. Any child tasks they spawn also run within the cgroup. This allows an administrator to manage an entire application as a single unit. An administrator can also configure allocations for the following resources:

- CPUsets
- Memory
- I/O
- Network (bandwidth)

Within CPUsets, cgroups allow administrators to configure the number of CPUs, affinity for specific CPUs or nodes [3], and the amount of CPU time used by a set of tasks. Using cgroups to configure CPUsets is vital for ensuring good overall performance, preventing an application from consuming excessive resources at the cost of other tasks while simultaneously ensuring that the application is not starved for CPU time.

I/O bandwidth and network bandwidth are managed by other resource controllers. Again, the resource controllers allow you to determine how much bandwidth the tasks in a cgroup can consume, and ensure that the tasks in a cgroup neither consume excessive resources nor are starved of resources.

Cgroups allow the administrator to define and allocate, at a high level, the system resources that various applications need (and will) consume. The system then automatically manages and balances the various applications, delivering good predictable performance and optimizing the performance of the overall system.

For more information on how to use control groups, refer to the *Resource Management Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

2.6. Storage and File System Improvements

Red Hat Enterprise Linux 6 also features several improvements to storage and file system management. Two of the most notable advances in this version are ext4 and XFS support. For more comprehensive coverage of performance improvements relating to storage and file systems, refer to Chapter 7, *File Systems*.

Ext4

Ext4 is the default file system for Red Hat Enterprise Linux 6. It is the fourth generation version of the EXT file system family, supporting a theoretical maximum file system size of 1 exabyte, and single file maximum size of 16TB. Red Hat Enterprise Linux 6 supports a maximum file system size of 16TB, and a single file maximum size of 16TB. Other than a much larger storage capacity, ext4 also includes several new features, such as:

- Extent-based metadata
- Delayed allocation
- Journal check-summing

For more information about the ext4 file system, refer to Section 7.3.1, “The Ext4 File System”.

XFS

XFS is a robust and mature 64-bit journaling file system that supports very large files and file systems on a single host. This file system was originally developed by SGI, and has a long history of running on extremely large servers and storage arrays. XFS features include:

- Delayed allocation
- Dynamically-allocated inodes
- B-tree indexing for scalability of free space management
- Online defragmentation and file system growing
- Sophisticated metadata read-ahead algorithms

While XFS scales to exabytes, the maximum XFS file system size supported by Red Hat is 100TB. For more information about XFS, refer to Section 7.3.2, “The XFS File System”.

Large Boot Drives

Traditional BIOS supports a maximum disk size of 2.2TB. Red Hat Enterprise Linux 6 systems using BIOS can support disks larger than 2.2TB by using a new disk structure called *Global Partition Table* (GPT). GPT can only be used for data disks; it cannot be used for boot drives with BIOS; therefore, boot drives can only be a maximum of 2.2TB in size. The BIOS was originally created for the IBM PC; while BIOS has evolved considerably to adapt to modern hardware, *Unified Extensible Firmware Interface* (UEFI) is designed to support new and emerging hardware.

Red Hat Enterprise Linux 6 also supports UEFI, which can be used to replace BIOS (still supported). Systems with UEFI running Red Hat Enterprise Linux 6 allow the use of GPT and 2.2TB (and larger) partitions for both boot partition and data partition.

Important — UEFI for 32-bit x86 systems

Red Hat Enterprise Linux 6 does not support UEFI for 32-bit x86 systems.

Important — UEFI for AMD64 and Intel 64

Note that the boot configurations of UEFI and BIOS differ significantly from each other. Therefore, the installed system must boot using the same firmware that was used during installation. You cannot install the operating system on a system that uses BIOS and then boot this installation on a system that uses UEFI.
Red Hat Enterprise Linux 6 supports version 2.2 of the UEFI specification. Hardware that supports version 2.3 of the UEFI specification or later should boot and operate with Red Hat Enterprise Linux 6, but the additional functionality defined by these later specifications will not be available. The UEFI specifications are available from http://www.uefi.org/specs/agreement/.

[3] A node is generally defined as a set of CPUs or cores within a socket.

Chapter 3. Monitoring and Analyzing System Performance

This chapter briefly introduces tools that can be used to monitor and analyze system and application performance, and points out the situations in which each tool is most useful. The data collected by each tool can reveal bottlenecks or other system problems that contribute to less-than-optimal performance.

3.1. The proc File System

The **proc** "file system" is a directory that contains a hierarchy of files that represent the current state of the Linux kernel. It allows applications and users to see the kernel's view of the system.

The **proc** directory also contains information about the hardware of the system, and any currently running processes. Most of these files are read-only, but some files (primarily those in **/proc/sys**) can be manipulated by users and applications to communicate configuration changes to the kernel.

For further information about viewing and editing files in the **proc** directory, refer to the *Deployment Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

3.2. GNOME and KDE System Monitors

The GNOME and KDE desktop environments both have graphical tools to assist you in monitoring and modifying the behavior of your system.

GNOME System Monitor

The **GNOME System Monitor** displays basic system information and allows you to monitor system processes, and resource or file system usage. Open it with the **gnome-system-monitor** command in the **Terminal**, or click on the **Applications** menu, and select **System Tools** > **System Monitor**.

GNOME System Monitor has four tabs:

System

Displays basic information about the computer's hardware and software.

Processes

Shows active processes, and the relationships between those processes, as well as detailed information about each process. It also lets you filter the processes displayed, and perform certain actions on those processes (start, stop, kill, change priority, etc.).

Resources

Displays the current CPU time usage, memory and swap space usage, and network usage.

File Systems

Lists all mounted file systems alongside some basic information about each, such as the file system type, mount point, and memory usage.

For further information about the **GNOME System Monitor**, refer to the **Help** menu in the application, or to the *Deployment Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

KDE System Guard

The **KDE System Guard** allows you to monitor current system load and processes that are running. It also lets you perform actions on processes. Open it with the **ksysguard** command in the **Terminal**, or click on the **Kickoff Application Launcher** and select **Applications** > **System** > **System Monitor**.

There are two tabs to **KDE System Guard**:

Process Table

Displays a list of all running processes, alphabetically by default. You can also sort processes by a number of other properties, including total CPU usage, physical or shared memory usage, owner, and priority. You can also filter the visible results, search for specific processes, or perform certain actions on a process.

System Load

Displays historical graphs of CPU usage, memory and swap space usage, and network usage. Hover over the graphs for detailed analysis and graph keys.

For further information about the **KDE System Guard**, refer to the **Help** menu in the application.

3.3. Built-in Command-line Monitoring Tools

In addition to graphical monitoring tools, Red Hat Enterprise Linux provides several tools that can be used to monitor a system from the command line. The advantage of these tools is that they can be used outside run level 5. This section discusses each tool briefly, and suggests the purposes to which each tool is best suited.

top

The **top** tool provides a dynamic, real-time view of the processes in a running system. It can display a variety of information, including a system summary and the tasks currently being managed by the Linux kernel. It also has a limited ability to manipulate processes. Both its operation and the information it displays are highly configurable, and any configuration details can be made to persist across restarts.

By default, the processes shown are ordered by the percentage of CPU usage, giving an easy view into the processes that are consuming the most resources.

For detailed information about using **top**, refer to its man page: **man top**.

ps

The **ps** tool takes a snapshot of a select group of active processes. By default this group is limited to processes owned by the current user and associated with the same terminal.

It can provide more detailed information about processes than **top**, but is not dynamic.

For detailed information about using **ps**, refer to its man page: **man ps**.

vmstat

vmstat (Virtual Memory Statistics) outputs instantaneous reports about your system's processes, memory, paging, block I/O, interrupts and CPU activity.

Although it is not dynamic like **top**, you can specify a sampling interval, which lets you observe system activity in near-real time.

For detailed information about using **vmstat**, refer to its man page: **man vmstat**.

sar

sar (System Activity Reporter) collects and reports information about today's system activity so far. The default output covers today's CPU utilization at ten minute intervals from the beginning of the day:

```
12:00:01 AM     CPU     %user     %nice   %system   %iowait    %steal     %idle
12:10:01 AM     all      0.10      0.00      0.15      2.96      0.00     96.79
12:20:01 AM     all      0.09      0.00      0.13      3.16      0.00     96.61
12:30:01 AM     all      0.09      0.00      0.14      2.11      0.00     97.66
...
```

This tool is a useful alternative to attempting to create periodic reports on system activity through **top** or similar tools.

For detailed information about using **sar**, refer to its man page: **man sar**.

3.4. Tuned and ktune

Tuned is a daemon that monitors and collects data on the usage of various system components, and uses that information to dynamically tune system settings as required. It can react to changes in CPU and network use, and adjust settings to improve performance in active devices or reduce power consumption in inactive devices.

The accompanying **ktune** partners with the **tuned-adm** tool to provide a number of tuning profiles that are pre-configured to enhance performance and reduce power consumption in a number of specific use cases. Edit these profiles or create new profiles to create performance solutions tailored to your environment.

The profiles provided as part of **tuned-adm** include:

default

The default power-saving profile. This is the most basic power-saving profile. It enables only the disk and CPU plug-ins. Note that this is not the same as turning **tuned-adm** off, where both **tuned** and **ktune** are disabled.

latency-performance

A server profile for typical latency performance tuning. This profile disables dynamic tuning mechanisms and transparent hugepages. It uses the **performance** governer for p-states through **cpuspeed**, and sets the I/O scheduler to **deadline**. Additionally, in Red Hat Enterprise Linux 6.5 and later, the profile requests a ***cpu_dma_latency*** value of **1**. In Red Hat Enterprise Linux 6.4 and earlier, **cpu_dma_latency** requested a value of **0**.

throughput-performance

A server profile for typical throughput performance tuning. This profile is recommended if the system does not have enterprise-class storage. throughput-performance disables power saving mechanisms and enables the **deadline** I/O scheduler. The CPU governor is set to **performance**. ***kernel.sched_min_granularity_ns*** (scheduler minimal preemption

granularity) is set to **10** milliseconds, ***kernel.sched_wakeup_granularity_ns*** (scheduler wake-up granularity) is set to **15** milliseconds, ***vm.dirty_ratio*** (virtual machine dirty ratio) is set to 40%, and transparent huge pages are enabled.

enterprise-storage

This profile is recommended for enterprise-sized server configurations with enterprise-class storage, including battery-backed controller cache protection and management of on-disk cache. It is the same as the **throughput-performance** profile, with one addition: file systems are re-mounted with **barrier=0**.

virtual-guest

This profile is optimized for virtual machines. It is based on the ***enterprise-storage*** profile, but also decreases the swappiness of virtual memory. This profile is available in Red Hat Enterprise Linux 6.3 and later.

virtual-host

Based on the ***enterprise-storage*** profile, ***virtual-host*** decreases the swappiness of virtual memory and enables more aggressive writeback of dirty pages. Non-root and non-boot file systems are mounted with **barrier=0**. Additionally, as of Red Hat Enterprise Linux 6.5, the ***kernel.sched_migration_cost*** parameter is set to **5** milliseconds. Prior to Red Hat Enterprise Linux 6.5, ***kernel.sched_migration_cost*** used the default value of **0.5** milliseconds.

Refer to the Red Hat Enterprise Linux 6 *Power Management Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/, for further information about **tuned** and **ktune**.

3.5. Application Profilers

Profiling is the process of gathering information about a program's behavior as it executes. You profile an application to determine which areas of a program can be optimized to increase the program's overall speed, reduce its memory usage, etc. Application profiling tools help to simplify this process.

There are three supported profiling tools for use with Red Hat Enterprise Linux 6: **SystemTap**, **OProfile** and **Valgrind**. Documenting these profiling tools is outside the scope of this guide; however, this section does provide links to further information and a brief overview of the tasks for which each profiler is suitable.

3.5.1. SystemTap

SystemTap is a tracing and probing tool that lets users monitor and analyze operating system activities (particularly kernel activities) in fine detail. It provides information similar to the output of tools like **netstat**, **top**, **ps** and **iostat**, but includes additional filtering and analysis options for the information that is collected.

SystemTap provides a deeper, more precise analysis of system activities and application behavior to allow you to pinpoint system and application bottlenecks.

The Function Callgraph plug-in for Eclipse uses SystemTap as a back-end, allowing it to thoroughly monitor the status of a program, including function calls, returns, times, and user-space variables, and

display the information visually for easy optimization.

For further information about SystemTap, refer to the *SystemTap Beginners Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

3.5.2. OProfile

OProfile (**oprofile**) is a system-wide performance monitoring tool. It uses the processor's dedicated performance monitoring hardware to retrieve information about the kernel and system executables, such as when memory is referenced, the number of L2 cache requests, and the number of hardware interrupts received. It can also be used to determine processor usage, and which applications and services are used most.

OProfile can also be used with Eclipse via the Eclipse OProfile plug-in. This plug-in allows users to easily determine the most time-consuming areas of their code, and perform all command-line functions of OProfile with rich visualization of the results.

However, users should be aware of several OProfile limitations:

- Performance monitoring samples may not be precise - because the processor may execute instructions out of order, a sample may be recorded from a nearby instruction, instead of the instruction that triggered the interrupt.
- Because OProfile is system-wide and expects processes to start and stop multiple times, samples from multiple runs are allowed to accumulate. This means you may need to clear sample data from previous runs.
- It focuses on identifying problems with CPU-limited processes, and therefore does not identify processes that are sleeping while they wait on locks for other events.

For further information about using OProfile, refer to the *Deployment Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/, or to the **oprofile** documentation on your system, located in **/usr/share/doc/oprofile-<*version*>**.

3.5.3. Valgrind

Valgrind provides a number of detection and profiling tools to help improve the performance and correctness of your applications. These tools can detect memory and thread-related errors as well as heap, stack and array overruns, allowing you to easily locate and correct errors in your application code. They can also profile the cache, the heap, and branch-prediction to identify factors that may increase application speed and minimize application memory use.

Valgrind analyzes your application by running it on a synthetic CPU and instrumenting the existing application code as it is executed. It then prints "commentary" clearly identifying each process involved in application execution to a user-specified file descriptor, file, or network socket. The level of instrumentation varies depending on the Valgrind tool in use, and its settings, but it is important to note that executing the instrumented code can take 4-50 times longer than normal execution.

Valgrind can be used on your application as-is, without recompiling. However, because Valgrind uses debugging information to pinpoint issues in your code, if your application and support libraries were not compiled with debugging information enabled, recompiling to include this information is highly recommended.

As of Red Hat Enterprise Linux 6.4, Valgrind integrates with *gdb* (GNU Project Debugger) to improve debugging efficiency.

More information about Valgrind is available from the *Developer Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/, or by using the **man**

valgrind command when the *valgrind* package is installed. Accompanying documentation can also be found in:

- **/usr/share/doc/valgrind-<version>/valgrind_manual.pdf**
- **/usr/share/doc/valgrind-<version>/html/index.html**

For information about how Valgrind can be used to profile system memory, refer to Section 5.3, “Using Valgrind to Profile Memory Usage”.

3.5.4. Perf

The **perf** tool provides a number of useful performance counters that let the user assess the impact of other commands on their system:

perf stat

This command provides overall statistics for common performance events, including instructions executed and clock cycles consumed. You can use the option flags to gather statistics on events other than the default measurement events. As of Red Hat Enterprise Linux 6.4, it is possible to use **perf stat** to filter monitoring based on one or more specified control groups (cgroups). For further information, read the man page: **man perf-stat**.

perf record

This command records performance data into a file which can be later analyzed using **perf report**. For further details, read the man page: **man perf-record**.

perf report

This command reads the performance data from a file and analyzes the recorded data. For further details, read the man page: **man perf-report**.

perf list

This command lists the events available on a particular machine. These events will vary based on the performance monitoring hardware and the software configuration of the system. For further information, read the man page: **man perf-list**.

perf top

This command performs a similar function to the **top** tool. It generates and displays a performance counter profile in realtime. For further information, read the man page: **man perf-top**.

perf trace

This command performs a similar function to the **strace** tool. It monitors the system calls used by a specified thread or process and all signals received by that application. Additional trace targets are available; refer to the man page for a full list.

More information about **perf** is available in the Red Hat Enterprise Linux *Developer Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

3.6. Red Hat Enterprise MRG

Red Hat Enterprise MRG's Realtime component includes **Tuna**, a tool that allows users to both adjust the tunable values their system and view the results of those changes. While it was developed for use with the Realtime component, it can also be used to tune standard Red Hat Enterprise Linux systems.

With Tuna, you can adjust or disable unnecessary system activity, including:

- BIOS parameters related to power management, error detection, and system management interrupts;
- network settings, such as interrupt coalescing, and the use of TCP;
- journaling activity in journaling file systems;
- system logging;
- whether interrupts and user processes are handled by a specific CPU or range of CPUs;
- whether swap space is used; and
- how to deal with out-of-memory exceptions.

For more detailed conceptual information about tuning Red Hat Enterprise MRG with the Tuna interface, refer to the "General System Tuning" chapter of the *Realtime Tuning Guide*. For detailed instructions about using the Tuna interface, refer to the *Tuna User Guide*. Both guides are available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_MRG/.

Chapter 4. CPU

The term CPU, which stands for *central processing unit*, is a misnomer for most systems, since *central* implies *single*, whereas most modern systems have more than one processing unit, or core. Physically, CPUs are contained in a package attached to a motherboard in a *socket*. Each socket on the motherboard has various connections: to other CPU sockets, memory controllers, interrupt controllers, and other peripheral devices. A socket to the operating system is a logical grouping of CPUs and associated resources. This concept is central to most of our discussions on CPU tuning.

Red Hat Enterprise Linux keeps a wealth of statistics about system CPU events; these statistics are useful in planning out a tuning strategy to improve CPU performance. Section 4.1.2, “Tuning CPU Performance” discusses some of the more useful statistics, where to find them, and how to analyze them for performance tuning.

Topology

Older computers had relatively few CPUs per system, which allowed an architecture known as *Symmetric Multi-Processor* (SMP). This meant that each CPU in the system had similar (or symmetric) access to available memory. In recent years, CPU count-per-socket has grown to the point that trying to give symmetric access to all RAM in the system has become very expensive. Most high CPU count systems these days have an architecture known as *Non-Uniform Memory Access* (NUMA) instead of SMP.

AMD processors have had this type of architecture for some time with their *Hyper Transport* (HT) interconnects, while Intel has begun implementing NUMA in their *Quick Path Interconnect* (QPI) designs. NUMA and SMP are tuned differently, since you need to account for the *topology* of the system when allocating resources for an application.

Threads

Inside the Linux operating system, the unit of execution is known as a *thread*. Threads have a register context, a stack, and a segment of executable code which they run on a CPU. It is the job of the operating system (OS) to schedule these threads on the available CPUs.

The OS maximizes CPU utilization by load-balancing the threads across available cores. Since the OS is primarily concerned with keeping CPUs busy, it does not make optimal decisions with respect to application performance. Moving an application thread to a CPU on another socket can worsen performance more than simply waiting for the current CPU to become available, since memory access operations can slow drastically across sockets. For high-performance applications, it is usually better for the designer to determine where threads are placed. Section 4.2, “CPU Scheduling” discusses how to best allocate CPUs and memory to best execute application threads.

Interrupts

One of the less obvious (but nonetheless important) system events that can impact application performance is the *interrupt* (also known as IRQs in Linux). These events are handled by the operating system, and are used by peripherals to signal the arrival of data or the completion of an operation, such as a network write or a timer event.

The manner in which the OS or CPU that is executing application code handles an interrupt does not affect the application's functionality. However, it can impact the performance of the application. This chapter also discusses tips on preventing interrupts from adversely impacting application performance.

4.1. CPU Topology

4.1.1. CPU and NUMA Topology

The first computer processors were *uniprocessors*, meaning that the system had a single CPU. The illusion of executing processes in parallel was done by the operating system rapidly switching the single CPU from one thread of execution (process) to another. In the quest for increasing system performance, designers noted that increasing the clock rate to execute instructions faster only worked up to a point (usually the limitations on creating a stable clock waveform with the current technology). In an effort to get more overall system performance, designers added another CPU to the system, allowing two parallel streams of execution. This trend of adding processors has continued over time.

Most early multiprocessor systems were designed so that each CPU had the same logical path to each memory location (usually a parallel bus). This let each CPU access any memory location in the same amount of time as any other CPU in the system. This type of architecture is known as a Symmetric Multi-Processor (SMP) system. SMP is fine for a small number of CPUs, but once the CPU count gets above a certain point (8 or 16), the number of parallel traces required to allow equal access to memory uses too much of the available board real estate, leaving less room for peripherals.

Two new concepts combined to allow for a higher number of CPUs in a system:

1. Serial buses
2. NUMA topologies

A serial bus is a single-wire communication path with a very high clock rate, which transfers data as packetized bursts. Hardware designers began to use serial buses as high-speed interconnects between CPUs, and between CPUs and memory controllers and other peripherals. This means that instead of requiring between 32 and 64 traces on the board from *each* CPU to the memory subsystem, there was now *one* trace, substantially reducing the amount of space required on the board.

At the same time, hardware designers were packing more transistors into the same space by reducing die sizes. Instead of putting individual CPUs directly onto the main board, they started packing them into a processor package as multi-core processors. Then, instead of trying to provide equal access to memory from each processor package, designers resorted to a Non-Uniform Memory Access (NUMA) strategy, where each package/socket combination has one or more dedicated memory area for high speed access. Each socket also has an interconnect to other sockets for slower access to the other sockets' memory.

As a simple NUMA example, suppose we have a two-socket motherboard, where each socket has been populated with a quad-core package. This means the total number of CPUs in the system is eight; four in each socket. Each socket also has an attached memory bank with four gigabytes of RAM, for a total system memory of eight gigabytes. For the purposes of this example, CPUs 0-3 are in socket 0, and CPUs 4-7 are in socket 1. Each socket in this example also corresponds to a NUMA node.

It might take three clock cycles for CPU 0 to access memory from bank 0: a cycle to present the address to the memory controller, a cycle to set up access to the memory location, and a cycle to read or write to the location. However, it might take six clock cycles for CPU 4 to access memory from the same location; because it is on a separate socket, it must go through two memory controllers: the local memory controller on socket 1, and then the remote memory controller on socket 0. If memory is contested on that location (that is, if more than one CPU is attempting to access the same location simultaneously), memory controllers need to arbitrate and serialize access to the memory, so memory access will take longer. Adding cache consistency (ensuring that local CPU caches contain the same data for the same memory location) complicates the process further.

The latest high-end processors from both Intel (Xeon) and AMD (Opteron) have NUMA topologies. The

AMD processors use an interconnect known as HyperTransport™ or HT, while Intel uses one named QuickPath Interconnect™ or QPI. The interconnects differ in how they physically connect to other interconnects, memory, or peripheral devices, but in effect they are a switch that allows transparent access to one connected device from another connected device. In this case, transparent refers to the fact that there is no special programming API required to use the interconnect, not a "no cost" option.

Because system architectures are so diverse, it is impractical to specifically characterize the performance penalty imposed by accessing non-local memory. We can say that each *hop* across an interconnect imposes at least some relatively constant performance penalty per hop, so referencing a memory location that is two interconnects from the current CPU imposes at least *2N + memory cycle time* units to access time, where N is the penalty per hop.

Given this performance penalty, performance-sensitive applications should avoid regularly accessing remote memory in a NUMA topology system. The application should be set up so that it stays on a particular node and allocates memory from that node.

To do this, there are a few things that applications will need to know:

1. What is the *topology* of the system?
2. Where is the application currently executing?
3. Where is the closest memory bank?

4.1.2. Tuning CPU Performance

Read this section to understand how to tune for better CPU performance, and for an introduction to several tools that aid in the process.

NUMA was originally used to connect a single processor to multiple memory banks. As CPU manufacturers refined their processes and die sizes shrank, multiple CPU cores could be included in one package. These CPU cores were clustered so that each had equal access time to a local memory bank, and cache could be shared between the cores; however, each 'hop' across an interconnect between core, memory, and cache involves a small performance penalty.

The example system in Figure 4.1, “Local and Remote Memory Access in NUMA Topology” contains two NUMA nodes. Each node has four CPUs, a memory bank, and a memory controller. Any CPU on a node has direct access to the memory bank on that node. Following the arrows on Node 1, the steps are as follows:

1. A CPU (any of 0-3) presents the memory address to the local memory controller.
2. The memory controller sets up access to the memory address.
3. The CPU performs read or write operations on that memory address.

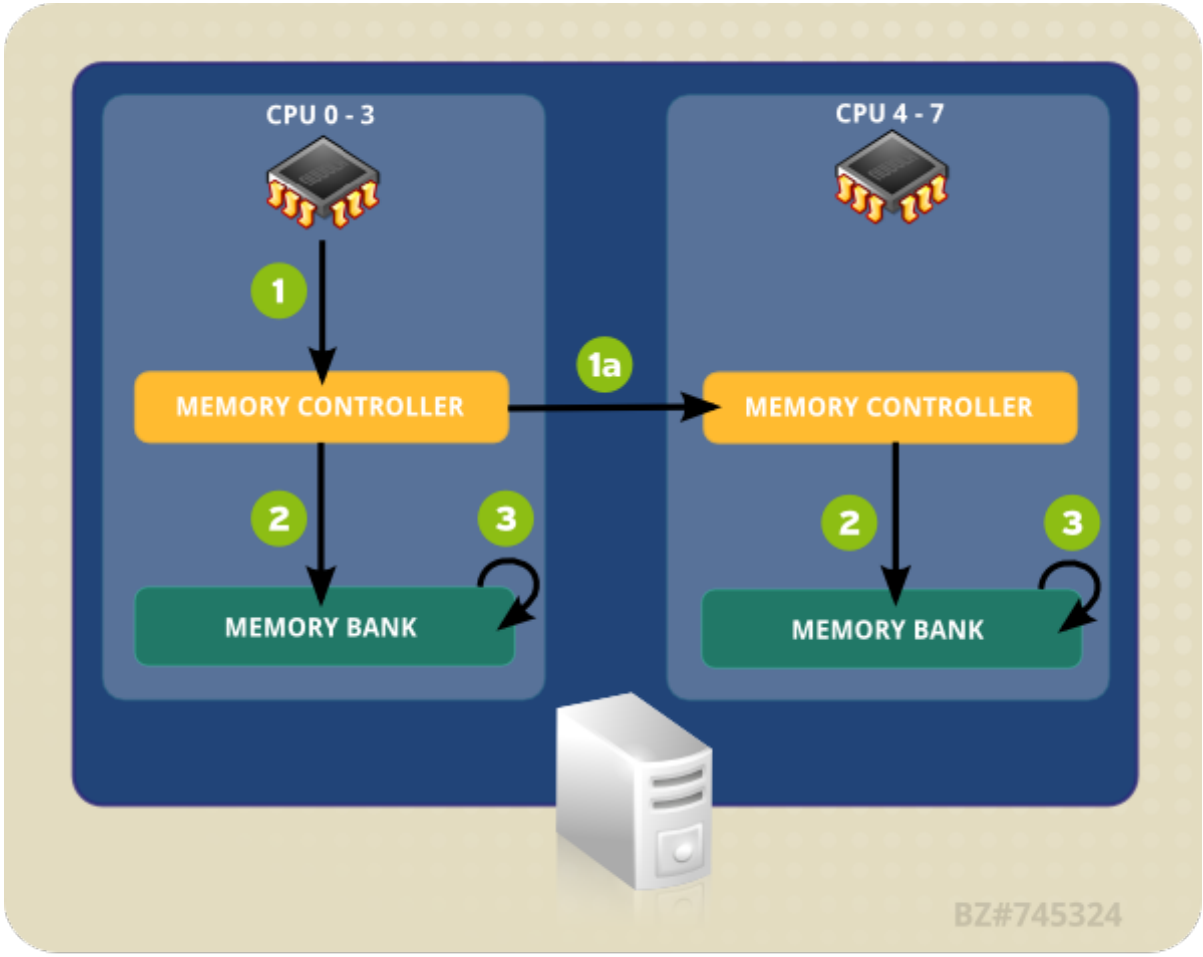


Figure 4.1. Local and Remote Memory Access in NUMA Topology

However, if a CPU on one node needs to access code that resides on the memory bank of a different NUMA node, the path it has to take is less direct:

1. A CPU (any of 0-3) presents the remote memory address to the local memory controller.
    a. The CPU's request for that remote memory address is passed to a remote memory controller, local to the node containing that memory address.
2. The remote memory controller sets up access to the remote memory address.
3. The CPU performs read or write operations on that remote memory address.

Every action needs to pass through multiple memory controllers, so access can take more than twice as long when attempting to access remote memory addresses. The primary performance concern in a multi-core system is therefore to ensure that information travels as efficiently as possible, via the shortest, or fastest, path.

To configure an application for optimal CPU performance, you need to know:

- the topology of the system (how its components are connected),
- the core on which the application executes, and
- the location of the closest memory bank.

Red Hat Enterprise Linux 6 ships with a number of tools to help you find this information and tune your system according to your findings. The following sections give an overview of useful tools for CPU

performance tuning.

4.1.2.1. Setting CPU Affinity with taskset

taskset retrieves and sets the CPU affinity of a running process (by process ID). It can also be used to launch a process with a given CPU affinity, which binds the specified process to a specified CPU or set of CPUs. However, **taskset** will not guarantee local memory allocation. If you require the additional performance benefits of local memory allocation, we recommend **numactl** over **taskset**; see Section 4.1.2.2, “Controlling NUMA Policy with **numactl**” for further details.

CPU affinity is represented as a bitmask. The lowest-order bit corresponds to the first logical CPU, and the highest-order bit corresponds to the last logical CPU. These masks are typically given in hexadecimal, so that **0x00000001** represents processor 0, and **0x00000003** represents processors 0 and 1.

To set the CPU affinity of a running process, execute the following command, replacing ***mask*** with the mask of the processor or processors you want the process bound to, and ***pid*** with the process ID of the process whose affinity you wish to change.

```
# taskset -p mask pid
```

To launch a process with a given affinity, run the following command, replacing ***mask*** with the mask of the processor or processors you want the process bound to, and ***program*** with the program, options, and arguments of the program you want to run.

```
# taskset mask -- program
```

Instead of specifying the processors as a bitmask, you can also use the **-c** option to provide a comma-delimited list of separate processors, or a range of processors, like so:

```
# taskset -c 0,5,7-9 -- myprogram
```

Further information about **taskset** is available from the man page: **man taskset**.

4.1.2.2. Controlling NUMA Policy with numactl

numactl runs processes with a specified scheduling or memory placement policy. The selected policy is set for that process and all of its children. **numactl** can also set a persistent policy for shared memory segments or files, and set the CPU affinity and memory affinity of a process. It uses the **/sys** file system to determine system topology.

The **/sys** file system contains information about how CPUs, memory, and peripheral devices are connected via NUMA interconnects. Specifically, the **/sys/devices/system/cpu** directory contains information about how a system's CPUs are connected to one another. The **/sys/devices/system/node** directory contains information about the NUMA nodes in the system, and the relative distances between those nodes.

In a NUMA system, the greater the distance between a processor and a memory bank, the slower the processor's access to that memory bank. Performance-sensitive applications should therefore be configured so that they allocate memory from the closest possible memory bank.

Performance-sensitive applications should also be configured to execute on a set number of cores, particularly in the case of multi-threaded applications. Because first-level caches are usually small, if multiple threads execute on one core, each thread will potentially evict cached data accessed by a previous thread. When the operating system attempts to multitask between these threads, and the

threads continue to evict each other's cached data, a large percentage of their execution time is spent on cache line replacement. This issue is referred to as *cache thrashing*. It is therefore recommended to bind a multi-threaded application to a node rather than a single core, since this allows the threads to share cache lines on multiple levels (first-, second-, and last-level cache) and minimizes the need for cache fill operations. However, binding an application to a single core may be performant if all threads are accessing the same cached data.

numactl allows you to bind an application to a particular core or NUMA node, and to allocate the memory associated with a core or set of cores to that application. Some useful options provided by numactl are:

--show

Display the NUMA policy settings of the current process. This parameter does not require further parameters, and can be used like so: **`numactl --show`**.

--hardware

Displays an inventory of the available nodes on the system.

--membind

Only allocate memory from the specified nodes. When this is in use, allocation will fail if memory on these nodes is insufficient. Usage for this parameter is **`numactl --membind=`*`nodes program`***, where ***nodes*** is the list of nodes you want to allocate memory from, and ***program*** is the program whose memory requirements should be allocated from that node. Node numbers can be given as a comma-delimited list, a range, or a combination of the two. Further details are available on the **numactl** man page: **`man numactl`**.

--cpunodebind

Only execute a command (and its child processes) on CPUs belonging to the specified node(s). Usage for this parameter is **`numactl --cpunodebind=`*`nodes program`***, where ***nodes*** is the list of nodes to whose CPUs the specified program (***program***) should be bound. Node numbers can be given as a comma-delimited list, a range, or a combination of the two. Further details are available on the **numactl** man page: **`man numactl`**.

--physcpubind

Only execute a command (and its child processes) on the specified CPUs. Usage for this parameter is **`numactl --physcpubind=`*`cpu program`***, where ***cpu*** is a comma-delimited list of physical CPU numbers as displayed in the processor fields of **`/proc/cpuinfo`**, and ***program*** is the program that should execute only on those CPUs. CPUs can also be specified relative to the current **`cpuset`**. Refer to the **numactl** man page for further information: **`man numactl`**.

--localalloc

Specifies that memory should always be allocated on the current node.

--preferred

Where possible, memory is allocated on the specified node. If memory cannot be allocated on the node specified, fall back to other nodes. This option takes only a single node number, like so: **`numactl --preferred=`*`node`***. Refer to the numactl man page for further information:

man numactl.

The **libnuma** library included in the *numactl* package offers a simple programming interface to the NUMA policy supported by the kernel. It is useful for more fine-grained tuning than the **numactl** utility. Further information is available on the man page: **man numa(7)**.

4.1.3. Hardware performance policy (x86_energy_perf_policy)

The *cpupowerutils* package includes **x86_energy_perf_policy**, a tool that allows administrators to define the relative importance of performance compared to energy efficiency. This information can then be used to influence processors that support this feature when they are selecting options that trade off between performance and energy efficiency. Processor support is indicated by **CPUID.06H.ECX.bit3**.

x86_energy_perf_policy requires root privileges, and operates on all CPUs by default.

To view the current policy, run the following command:

```
# x86_energy_perf_policy -r
```

To set a new policy, run the following command:

```
# x86_energy_perf_policy profile_name
```

Replace ***profile_name*** with one of the following profiles.

performance

The processor is unwilling to sacrifice any performance for the sake of saving energy. This is the default value.

normal

The processor tolerates minor performance compromises for potentially significant energy savings. This is a reasonable setting for most desktops and servers.

powersave

The processor accepts potentially significant hits to performance in order to maximise energy efficiency.

For further information about this tool, refer to the man page: **man x86_energy_perf_policy**.

4.1.4. turbostat

The **turbostat** tool is part of the *cpupowerutils* package. It reports processor topology, frequency, idle power-state statistics, temperature, and power usage on Intel 64 processors.

Turbostat can help administrators to identify servers that use more power than necessary, do not enter deep sleep states when expected, or are idle enough to consider virtualizing if a platform is readily available (thus allowing the physical server to be decommissioned). It can also help administrators to identify the rate of system management interrupts (SMIs), and any latency-sensitive applications that may be prompting SMIs unnecessarily. Turbostat can also be used in conjunction with the **powertop** utility to identify services that may be preventing the processor from entering deep sleep states.

Turbostat requires **root** privileges to run. It also requires processor support for invariant time stamp counters, and APERF and MPERF model-specific registers.

By default, **turbostat** prints a summary of counter results for the entire system, followed by counter results every 5 seconds, under the following headings:

pkg
The processor package number.

core
The processor core number.

CPU
The Linux CPU (logical processor) number.

%c0
The percentage of the interval for which the CPU retired instructions.

GHz
The average clock speed while the CPU was in the c0 state.

TSC
The average clock speed over the course of the entire interval.

%c1, %c3, and %c6
The percentage of the interval for which the processor was in the c1, c3, or c6 state, respectively.

%pc3 or %pc6
The percentage of the interval for which the processor was in the pc3 or pc6 state, respectively.

Specify a different period between counter results with the ***-i*** option, for example, run **turbostat -i 10** to print results every 10 seconds instead.

Note

Upcoming Intel processors may add additional C-states. As of Red Hat Enterprise Linux 6.5, turbostat provides support for the c7, c8, c9, and c10 states.

For more information about **turbostat**, refer to the man page: **man turbostat**.

Important

Previously, the **numastat** tool was a Perl script written by Andi Kleen. It has been significantly rewritten for Red Hat Enterprise Linux 6.4.
While the default command (**numastat**, with no options or parameters) maintains strict compatibility with the previous version of the tool, note that supplying options or parameters to this command significantly changes both the output content and its format.

numastat displays memory statistics (such as allocation hits and misses) for processes and the operating system on a per-NUMA-node basis. By default, running **numastat** displays how many pages of memory are occupied by the following event categories for each node.

Optimal CPU performance is indicated by low **numa_miss** and **numa_foreign** values.

This updated version of **numastat** also shows whether process memory is spread across a system or centralized on specific nodes using **numactl**.

Cross-reference **numastat** output with per-CPU **top** output to verify that process threads are running on the same nodes to which memory is allocated.

Default Tracking Categories

numa_hit
The number of attempted allocations to this node that were successful.

numa_miss
The number of attempted allocations to another node that were allocated on this node because of low memory on the intended node. Each **numa_miss** event has a corresponding **numa_foreign** event on another node.

numa_foreign
The number of allocations initially intended for this node that were allocated to another node instead. Each **numa_foreign** event has a corresponding **numa_miss** event on another node.

interleave_hit
The number of attempted interleave policy allocations to this node that were successful.

local_node
The number of times a process on this node successfully allocated memory on this node.

other_node
The number of times a process on another node allocated memory on this node.

Supplying any of the following options changes the displayed units to megabytes of memory (rounded to two decimal places), and changes other specific **numastat** behaviors as described below.

-c

Horizontally condenses the displayed table of information. This is useful on systems with a large number of NUMA nodes, but column width and inter-column spacing are somewhat unpredictable. When this option is used, the amount of memory is rounded to the nearest megabyte.

-m

Displays system-wide memory usage information on a per-node basis, similar to the information found in **/proc/meminfo**.

-n

Displays the same information as the original **numastat** command (numa_hit, numa_miss, numa_foreign, interleave_hit, local_node, and other_node), with an updated format, using megabytes as the unit of measurement.

-p *pattern*

Displays per-node memory information for the specified pattern. If the value for ***pattern*** is comprised of digits, **numastat** assumes that it is a numerical process identifier. Otherwise, **numastat** searches process command lines for the specified pattern.

Command line arguments entered after the value of the **-p** option are assumed to be additional patterns for which to filter. Additional patterns expand, rather than narrow, the filter.

-s

Sorts the displayed data in descending order so that the biggest memory consumers (according to the **total** column) are listed first.

Optionally, you can specify a ***node***, and the table will be sorted according to the ***node*** column. When using this option, the ***node*** value must follow the **-s** option immediately, as shown here:

```
numastat -s2
```

Do not include white space between the option and its value.

-v

Displays more verbose information. Namely, process information for multiple processes will display detailed information for each process.

-V

Displays **numastat** version information.

-z

Omits table rows and columns with only zero values from the displayed information. Note that some near-zero values that are rounded to zero for display purposes will not be omitted from the displayed output.

4.1.6. NUMA Affinity Management Daemon (numad)

numad is an automatic NUMA affinity management daemon. It monitors NUMA topology and resource usage within a system in order to dynamically improve NUMA resource allocation and management (and therefore system performance).

Depending on system workload, **numad** can provide benchmark performance improvements of up to 50%. To achieve these performance gains, **numad** periodically accesses information from the **/proc** file system to monitor available system resources on a per-node basis. The daemon then attempts to place significant processes on NUMA nodes that have sufficient aligned memory and CPU resources for optimum NUMA performance. Current thresholds for process management are at least 50% of one CPU and at least 300 MB of memory. **numad** attempts to maintain a resource utilization level, and rebalances allocations when necessary by moving processes between NUMA nodes.

numad also provides a pre-placement advice service that can be queried by various job management systems to provide assistance with the initial binding of CPU and memory resources for their processes. This pre-placement advice service is available regardless of whether **numad** is running as a daemon on the system. Refer to the man page for further details about using the **-w** option for pre-placement advice: **man numad**.

4.1.6.1. Benefits of numad

numad primarily benefits systems with long-running processes that consume significant amounts of resources, particularly when these processes are contained in a subset of the total system resources.

numad may also benefit applications that consume multiple NUMA nodes' worth of resources. However, the benefits that **numad** provides decrease as the percentage of consumed resources on a system increases.

numad is unlikely to improve performance when processes run for only a few minutes, or do not consume many resources. Systems with continuous unpredictable memory access patterns, such as large in-memory databases, are also unlikely to benefit from **numad** use.

4.1.6.2. Modes of operation

Note

If KSM is in use, change the **/sys/kernel/mm/ksm/merge_nodes** tunable to **0** to avoid merging pages across NUMA nodes. Kernel memory accounting statistics can eventually contradict each other after large amounts of cross-node merging. As such, **numad** can become confused after the KSM daemon merges large amounts of memory. If your system has a large amount of free memory, you may achieve higher performance by turning off and disabling the KSM daemon.

numad can be used in two ways:

- as a service
- as an executable

4.1.6.2.1. Using numad as a service

While the **numad** service runs, it will attempt to dynamically tune the system based on its workload.

To start the service, run:

```
# service numad start
```

To make the service persist across reboots, run:

```
# chkconfig numad on
```

4.1.6.2.2. Using numad as an executable

To use **numad** as an executable, just run:

```
# numad
```

numad will run until it is stopped. While it runs, its activities are logged in **/var/log/numad.log**.

To restrict **numad** management to a specific process, start it with the following options.

```
# numad -S 0 -p pid
```

-p pid

Adds the specified ***pid*** to an explicit inclusion list. The process specified will not be managed until it meets the **numad** process significance threshold.

-S mode

The ***-S*** parameter specifies the type of process scanning. Setting it to **0** as shown limits **numad** management to explicitly included processes.

To stop **numad**, run:

```
# numad -i 0
```

Stopping **numad** does not remove the changes it has made to improve NUMA affinity. If system use changes significantly, running **numad** again will adjust affinity to improve performance under the new conditions.

For further information about available **numad** options, refer to the **numad** man page: **man numad**.

4.2. CPU Scheduling

The *scheduler* is responsible for keeping the CPUs in the system busy. The Linux scheduler implements a number of *scheduling policies*, which determine when and for how long a thread runs on a particular CPU core.

Scheduling policies are divided into two major categories:

1. Realtime policies
   - SCHED_FIFO
   - SCHED_RR
2. Normal policies
   - SCHED_OTHER
   - SCHED_BATCH
   - SCHED_IDLE

4.2.1. Realtime scheduling policies

Realtime threads are scheduled first, and normal threads are scheduled after all realtime threads have been scheduled.

The *realtime* policies are used for time-critical tasks that must complete without interruptions.

SCHED_FIFO

This policy is also referred to as *static priority scheduling*, because it defines a fixed priority (between 1 and 99) for each thread. The scheduler scans a list of SCHED_FIFO threads in priority order and schedules the highest priority thread that is ready to run. This thread runs until it blocks, exits, or is preempted by a higher priority thread that is ready to run.

Even the lowest priority realtime thread will be scheduled ahead of any thread with a non-realtime policy; if only one realtime thread exists, the **SCHED_FIFO** priority value does not matter.

SCHED_RR

A round-robin variant of the **SCHED_FIFO** policy. **SCHED_RR** threads are also given a fixed priority between 1 and 99. However, threads with the same priority are scheduled round-robin style within a certain quantum, or time slice. The **sched_rr_get_interval(2)** system call returns the value of the time slice, but the duration of the time slice cannot be set by a user. This policy is useful if you need multiple thread to run at the same priority.

For more detailed information about the defined semantics of the realtime scheduling policies, refer to the *IEEE 1003.1 POSIX standard* under System Interfaces — Realtime, which is available from http://pubs.opengroup.org/onlinepubs/009695399/functions/xsh_chap02_08.html.

Best practice in defining thread priority is to start low and increase priority only when a legitimate latency is identified. Realtime threads are not time-sliced like normal threads; **SCHED_FIFO** threads run until they block, exit, or are pre-empted by a thread with a higher priority. Setting a priority of 99 is therefore not recommended, as this places your process at the same priority level as migration and watchdog threads. If these threads are blocked because your thread goes into a computational loop, they will not be able to run. Uniprocessor systems will eventually lock up in this situation.

In the Linux kernel, the **SCHED_FIFO** policy includes a bandwidth cap mechanism. This protects realtime application programmers from realtime tasks that might monopolize the CPU. This mechanism can be adjusted through the following **/proc** file system parameters:

/proc/sys/kernel/sched_rt_period_us

Defines the time period to be considered one hundred percent of CPU bandwidth, in microseconds ('us' being the closest equivalent to 'µs' in plain text). The default value is 1000000µs, or 1 second.

/proc/sys/kernel/sched_rt_runtime_us

Defines the time period to be devoted to running realtime threads, in microseconds ('us' being the closest equivalent to 'µs' in plain text). The default value is 950000µs, or 0.95 seconds.

4.2.2. Normal scheduling policies

There are three normal scheduling policies: **SCHED_OTHER**, **SCHED_BATCH** and **SCHED_IDLE**. However, the **SCHED_BATCH** and **SCHED_IDLE** policies are intended for very low priority jobs, and as such are of limited interest in a performance tuning guide.

SCHED_OTHER, or SCHED_NORMAL

The default scheduling policy. This policy uses the Completely Fair Scheduler (CFS) to provide fair access periods for all threads using this policy. CFS establishes a dynamic priority list partly based on the ***niceness*** value of each process thread. (Refer to the *Deployment Guide* for more details about this parameter and the **/proc** file system.) This gives users some indirect level of control over process priority, but the dynamic priority list can only be directly changed by the CFS.

4.2.3. Policy Selection

Selecting the correct scheduler policy for an application's threads is not always a straightforward task. In general, realtime policies should be used for time critical or important tasks that need to be scheduled quickly and do not run for extended periods of time. Normal policies will generally yield better data throughput results than realtime policies because they let the scheduler run threads more efficiently (that is, they do not need to reschedule for pre-emption as often).

If you are managing large numbers of threads and are concerned mainly with data throughput (network packets per second, writes to disk, etc.) then use **SCHED_OTHER** and let the system manage CPU utilization for you.

If you are concerned with event response time (latency) then use **SCHED_FIFO**. If you have a small number of threads, consider isolating a CPU socket and moving your threads onto that socket's cores so that there are no other threads competing for time on the cores.

4.3. Interrupts and IRQ Tuning

An interrupt request (IRQ) is a request for service, sent at the hardware level. Interrupts can be sent by either a dedicated hardware line, or across a hardware bus as an information packet (a Message Signaled Interrupt, or MSI).

When interrupts are enabled, receipt of an IRQ prompts a switch to interrupt context. Kernel interrupt dispatch code retrieves the IRQ number and its associated list of registered Interrupt Service Routines (ISRs), and calls each ISR in turn. The ISR acknowledges the interrupt and ignores redundant interrupts from the same IRQ, then queues a deferred handler to finish processing the interrupt and stop the ISR from ignoring future interrupts.

The **/proc/interrupts** file lists the number of interrupts per CPU per I/O device. It displays the IRQ number, the number of that interrupt handled by each CPU core, the interrupt type, and a comma-delimited list of drivers that are registered to receive that interrupt. (Refer to the proc(5) man page for further details: **man 5 proc**)

IRQs have an associated "affinity" property, ***smp_affinity***, which defines the CPU cores that are allowed to execute the ISR for that IRQ. This property can be used to improve application performance by assigning both interrupt affinity and the application's thread affinity to one or more specific CPU cores. This allows cache line sharing between the specified interrupt and application threads.

The interrupt affinity value for a particular IRQ number is stored in the associated **/proc/irq/*IRQ_NUMBER*/smp_affinity** file, which can be viewed and modified by the root user. The value stored in this file is a hexadecimal bit-mask representing all CPU cores in the system.

As an example, to set the interrupt affinity for the Ethernet driver on a server with four CPU cores, first determine the IRQ number associated with the Ethernet driver:

```
# grep eth0 /proc/interrupts
32:   0     140      45       850264      PCI-MSI-edge      eth0
```

Use the IRQ number to locate the appropriate ***smp_affinity*** file:

```
# cat /proc/irq/32/smp_affinity
f
```

The default value for smp_affinity is **f**, meaning that the IRQ can be serviced on any of the CPUs in the system. Setting this value to **1**, as follows, means that only CPU 0 can service this interrupt:

```
# echo 1 >/proc/irq/32/smp_affinity
# cat /proc/irq/32/smp_affinity
1
```

Commas can be used to delimit ***smp_affinity*** values for discrete 32-bit groups. This is required on systems with more than 32 cores. For example, the following example shows that IRQ 40 is serviced on all cores of a 64-core system:

```
# cat /proc/irq/40/smp_affinity
ffffffff,ffffffff
```

To service IRQ 40 on only the upper 32-cores of a 64-core system, you would do the following:

```
# echo 0xffffffff,00000000 > /proc/irq/40/smp_affinity
# cat /proc/irq/40/smp_affinity
ffffffff,00000000
```

Note

On systems that support *interrupt steering*, modifying the ***smp_affinity*** of an IRQ sets up the hardware so that the decision to service an interrupt with a particular CPU is made at the hardware level, with no intervention from the kernel.

4.4. Enhancements to NUMA in Red Hat Enterprise Linux 6

Red Hat Enterprise Linux 6 includes a number of enhancements to capitalize on the full potential of today's highly scalable hardware. This section gives a high-level overview of the most important NUMA-related performance enhancements provided by Red Hat Enterprise Linux 6.

4.4.1. Bare-metal and Scalability Optimizations

4.4.1.1. Enhancements in topology-awareness

The following enhancements allow Red Hat Enterprise Linux to detect low-level hardware and architecture details, improving its ability to automatically optimize processing on your system.

enhanced topology detection

This allows the operating system to detect low-level hardware details (such as logical CPUs, hyper threads, cores, sockets, NUMA nodes and access times between nodes) at boot time, and optimize processing on your system.

completely fair scheduler

This new scheduling mode ensures that runtime is shared evenly between eligible processes. Combining this with topology detection allows processes to be scheduled onto CPUs within the same socket to avoid the need for expensive remote memory access, and ensure that cache content is preserved wherever possible.

`malloc`

`malloc` is now optimized to ensure that the regions of memory that are allocated to a process are as physically close as possible to the core on which the process is executing. This increases memory access speeds.

skbuff I/O buffer allocation

Similarly to **`malloc`**, this is now optimized to use memory that is physically close to the CPU handling I/O operations such as device interrupts.

device interrupt affinity

Information recorded by device drivers about which CPU handles which interrupts can be used to restrict interrupt handling to CPUs within the same physical socket, preserving cache affinity and limiting high-volume cross-socket communication.

4.4.1.2. Enhancements in Multi-processor Synchronization

Coordinating tasks between multiple processors requires frequent, time-consuming operations to ensure that processes executing in parallel do not compromise data integrity. Red Hat Enterprise Linux includes the following enhancements to improve performance in this area:

Read-Copy-Update (RCU) locks

Typically, 90% of locks are acquired for read-only purposes. RCU locking removes the need to obtain an exclusive-access lock when the data being accessed is not being modified. This locking mode is now used in page cache memory allocation: locking is now used only for allocation or deallocation operations.

per-CPU and per-socket algorithms

Many algorithms have been updated to perform lock coordination among cooperating CPUs on the same socket to allow for more fine-grained locking. Numerous global spinlocks have been replaced with per-socket locking methods, and updated memory allocator zones and related memory page lists allow memory allocation logic to traverse a more efficient subset of the memory mapping data structures when performing allocation or deallocation operations.

4.4.2. Virtualization Optimizations

Because KVM utilizes kernel functionality, KVM-based virtualized guests immediately benefit from all bare-metal optimizations. Red Hat Enterprise Linux also includes a number of enhancements to allow

virtualized guests to approach the performance level of a bare-metal system. These enhancements focus on the I/O path in storage and network access, allowing even intensive workloads such as database and file-serving to make use of virtualized deployment. NUMA-specific enhancements that improve the performance of virtualized systems include:

CPU pinning

Virtual guests can be bound to run on a specific socket in order to optimize local cache use and remove the need for expensive inter-socket communications and remote memory access.

transparent hugepages (THP)

With THP enabled, the system automatically performs NUMA-aware memory allocation requests for large contiguous amounts of memory, reducing both lock contention and the number of translation lookaside buffer (TLB) memory management operations required and yielding a performance increase of up to 20% in virtual guests.

kernel-based I/O implementation

The virtual guest I/O subsystem is now implemented in the kernel, greatly reducing the expense of inter-node communication and memory access by avoiding a significant amount of context switching, and synchronization and communication overhead.

Chapter 5. Memory

Read this chapter for an overview of the memory management features available in Red Hat Enterprise Linux, and how to use these management features to optimize memory utilization in your system.

5.1. Huge Translation Lookaside Buffer (HugeTLB)

Physical memory addresses are translated to virtual memory addresses as part of memory management. The mapped relationship of physical to virtual addresses is stored in a data structure known as the page table. Since reading the page table for every address mapping would be time consuming and resource-expensive, there is a cache for recently-used addresses. This cache is called the Translation Lookaside Buffer (TLB).

However, the TLB can only cache so many address mappings. If a requested address mapping is not in the TLB, the page table must still be read to determine the physical to virtual address mapping. This is known as a "TLB miss". Applications with large memory requirements are more likely to be affected by TLB misses than applications with minimal memory requirements because of the relationship between their memory requirements and the size of the pages used to cache address mappings in the TLB. Since each miss involves reading the page table, it is important to avoid these misses wherever possible.

The Huge Translation Lookaside Buffer (HugeTLB) allows memory to be managed in very large segments so that more address mappings can be cached at one time. This reduces the probability of TLB misses, which in turn improves performance in applications with large memory requirements.

Information about configuring the HugeTLB can be found in the kernel documentation: **/usr/share/doc/kernel-doc-*version*/Documentation/vm/hugetlbpage.txt**

5.2. Huge Pages and Transparent Huge Pages

Memory is managed in blocks known as *pages*. A page is 4096 bytes. 1MB of memory is equal to 256 pages; 1GB of memory is equal to 256,000 pages, etc. CPUs have a built-in *memory management unit* that contains a list of these pages, with each page referenced through a *page table entry*.

There are two ways to enable the system to manage large amounts of memory:

- Increase the number of page table entries in the hardware memory management unit
- Increase the page size

The first method is expensive, since the hardware memory management unit in a modern processor only supports hundreds or thousands of page table entries. Additionally, hardware and memory management algorithms that work well with thousands of pages (megabytes of memory) may have difficulty performing well with millions (or even billions) of pages. This results in performance issues: when an application needs to use more memory pages than the memory management unit supports, the system falls back to slower, software-based memory management, which causes the entire system to run more slowly.

Red Hat Enterprise Linux 6 implements the second method via the use of *huge pages*.

Simply put, huge pages are blocks of memory that come in 2MB and 1GB sizes. The page tables used by the 2MB pages are suitable for managing multiple gigabytes of memory, whereas the page tables of 1GB pages are best for scaling to terabytes of memory.

Huge pages must be assigned at boot time. They are also difficult to manage manually, and often require significant changes to code in order to be used effectively. As such, Red Hat Enterprise Linux 6 also implemented the use of *transparent huge pages* (THP). THP is an abstraction layer that automates

most aspects of creating, managing, and using huge pages.

THP hides much of the complexity in using huge pages from system administrators and developers. As the goal of THP is improving performance, its developers (both from the community and Red Hat) have tested and optimized THP across a wide range of systems, configurations, applications, and workloads. This allows the default settings of THP to improve the performance of most system configurations.

Note that THP can currently only map anonymous memory regions such as heap and stack space.

5.3. Using Valgrind to Profile Memory Usage

Valgrind is a framework that provides instrumentation to user-space binaries. It ships with a number of tools that can be used to profile and analyze program performance. The tools outlined in this section provide analysis that can aid in the detection of memory errors such as the use of uninitialized memory and improper allocation or deallocation of memory. All are included in the *valgrind* package, and can be run with the following command:

```
valgrind --tool=toolname program
```

Replace ***toolname*** with the name of the tool you wish to use (for memory profiling, **memcheck**, **massif**, or **cachegrind**), and ***program*** with the program you wish to profile with Valgrind. Be aware that Valgrind's instrumentation will cause your program to run more slowly than it would normally.

An overview of Valgrind's capabilities is provided in Section 3.5.3, “Valgrind”. Further details, including information about available plugins for Eclipse, are included in the *Developer Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/. Accompanying documentation can be viewed with the **man valgrind** command when the *valgrind* package is installed, or found in the following locations:

- **/usr/share/doc/valgrind-*version*/valgrind_manual.pdf**, and
- **/usr/share/doc/valgrind-*version*/html/index.html**.

5.3.1. Profiling Memory Usage with Memcheck

Memcheck is the default Valgrind tool, and can be run with **valgrind *program***, without specifying **--tool=memcheck**. It detects and reports on a number of memory errors that can be difficult to detect and diagnose, such as memory access that should not occur, the use of undefined or uninitialized values, incorrectly freed heap memory, overlapping pointers, and memory leaks. Programs run ten to thirty times more slowly with Memcheck than when run normally.

Memcheck returns specific errors depending on the type of issue it detects. These errors are outlined in detail in the Valgrind documentation included at **/usr/share/doc/valgrind-*version*/valgrind_manual.pdf**.

Note that Memcheck can only report these errors — it cannot prevent them from occurring. If your program accesses memory in a way that would normally result in a segmentation fault, the segmentation fault still occurs. However, Memcheck will log an error message immediately prior to the fault.

Memcheck provides command line options that can be used to focus the checking process. Some of the options available are:

--leak-check

When enabled, Memcheck searches for memory leaks when the client program finishes. The default value is **summary**, which outputs the number of leaks found. Other possible values are

yes and **full**, both of which give details of each individual leak, and **no**, which disables memory leak checking.

--undef-value-errors

When enabled (set to **yes**), Memcheck reports errors when undefined values are used. When disabled (set to **no**), undefined value errors are not reported. This is enabled by default. Disabling it speeds up Memcheck slightly.

--ignore-ranges

Allows the user to specify one or more ranges that Memcheck should ignore when checking for addressability. Multiple ranges are delimited by commas, for example, **--ignore-ranges=0xPP-0xQQ,0xRR-0xSS**.

For a full list of options, refer to the documentation included at **/usr/share/doc/valgrind-*version*/valgrind_manual.pdf**.

5.3.2. Profiling Cache Usage with Cachegrind

Cachegrind simulates your program's interaction with a machine's cache hierarchy and (optionally) branch predictor. It tracks usage of the simulated first-level instruction and data caches to detect poor code interaction with this level of cache; and the last-level cache, whether that is a second- or third-level cache, in order to track access to main memory. As such, programs run with Cachegrind run twenty to one hundred times slower than when run normally.

To run Cachegrind, execute the following command, replacing ***program*** with the program you wish to profile with Cachegrind:

```
# valgrind --tool=cachegrind program
```

Cachegrind can gather the following statistics for the entire program, and for each function in the program:

- first-level instruction cache reads (or instructions executed) and read misses, and last-level cache instruction read misses;
- data cache reads (or memory reads), read misses, and last-level cache data read misses;
- data cache writes (or memory writes), write misses, and last-level cache write misses;
- conditional branches executed and mispredicted; and
- indirect branches executed and mispredicted.

Cachegrind prints summary information about these statistics to the console, and writes more detailed profiling information to a file (**cachegrind.out.*pid*** by default, where ***pid*** is the process ID of the program on which you ran Cachegrind). This file can be further processed by the accompanying **cg_annotate** tool, like so:

```
# cg_annotate cachegrind.out.pid
```

Note

cg_annotate can output lines longer than 120 characters, depending on the length of the path. To make the output clearer and easier to read, we recommend making your terminal window at least this wide before executing the aforementioned command.

You can also compare the profile files created by Cachegrind to make it simpler to chart program performance before and after a change. To do so, use the **cg_diff** command, replacing ***first*** with the initial profile output file, and ***second*** with the subsequent profile output file:

```
# cg_diff first second
```

This command produces a combined output file, which can be viewed in more detail with **cg_annotate**.

Cachegrind supports a number of options to focus its output. Some of the options available are:

--I1

Specifies the size, associativity, and line size of the first-level instruction cache, separated by commas: **--I1=*size*,*associativity*,*line size***.

--D1

Specifies the size, associativity, and line size of the first-level data cache, separated by commas: **--D1=*size*,*associativity*,*line size***.

--LL

Specifies the size, associativity, and line size of the last-level cache, separated by commas: **--LL=*size*,*associativity*,*line size***.

--cache-sim

Enables or disables the collection of cache access and miss counts. The default value is **yes** (enabled).

Note that disabling both this and **--branch-sim** leaves Cachegrind with no information to collect.

--branch-sim

Enables or disables the collection of branch instruction and misprediction counts. This is set to **no** (disabled) by default, since it slows Cachegrind by approximately 25 per-cent.

Note that disabling both this and **--cache-sim** leaves Cachegrind with no information to collect.

For a full list of options, refer to the documentation included at **/usr/share/doc/valgrind-*version*/valgrind_manual.pdf**.

5.3.3. Profiling Heap and Stack Space with Massif

Massif measures the heap space used by a specified program; both the useful space, and any additional space allocated for book-keeping and alignment purposes. It can help you reduce the amount of memory used by your program, which can increase your program's speed, and reduce the likelihood that your program will exhaust the swap space of the machine on which it executes. Massif can also provide details about which parts of your program are responsible for allocating heap memory. Programs run with Massif run about twenty times more slowly than their normal execution speed.

To profile the heap usage of a program, specify **massif** as the Valgrind tool you wish to use:

```
# valgrind --tool=massif program
```

Profiling data gathered by Massif is written to a file, which by default is called **massif.out.*pid***, where ***pid*** is the process ID of the specified ***program***.

This profiling data can also be graphed with the **ms_print** command, like so:

```
# ms_print massif.out.pid
```

This produces a graph showing memory consumption over the program's execution, and detailed information about the sites responsible for allocation at various points in the program, including at the point of peak memory allocation.

Massif provides a number of command line options that can be used to direct the output of the tool. Some of the available options are:

--heap

Specifies whether to perform heap profiling. The default value is **yes**. Heap profiling can be disabled by setting this option to **no**.

--heap-admin

Specifies the number of bytes per block to use for administration when heap profiling is enabled. The default value is **8** bytes per block.

--stacks

Specifies whether to perform stack profiling. The default value is **no** (disabled). To enable stack profiling, set this option to **yes**, but be aware that doing so will greatly slow Massif. Also note that Massif assumes that the main stack has size zero at start-up in order to better indicate the size of the stack portion over which the program being profiled has control.

--time-unit

Specifies the unit of time used for the profiling. There are three valid values for this option: instructions executed (**i**), the default value, which is useful in most cases; real time (**ms**, in milliseconds), which can be useful in certain instances; and bytes allocated/deallocated on the heap and/or stack (**B**), which is useful for very short-run programs, and for testing purposes, because it is the most reproducible across different machines. This option is useful when graphing Massif output with **ms_print**.

For a full list of options, refer to the documentation included at **/usr/share/doc/valgrind-*version*/valgrind_manual.pdf**.

5.4. Capacity Tuning

Read this section for an outline of memory, kernel and file system capacity, the parameters related to each, and the trade-offs involved in adjusting these parameters.

To set these values temporarily during tuning, echo the desired value to the appropriate file in the proc file system. For example, to set ***overcommit_memory*** temporarily to **1**, run:

```
# echo 1 > /proc/sys/vm/overcommit_memory
```

Note that the path to the parameter in the proc file system varies depending on the system affected by the change.

To set these values persistently, you will need to use the **sysctl** command. For further details, refer to the *Deployment Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

Capacity-related Memory Tunables

Each of the following parameters is located under **/proc/sys/vm/** in the proc file system.

overcommit_memory

Defines the conditions that determine whether a large memory request is accepted or denied. There are three possible values for this parameter:

- **0** — The default setting. The kernel performs heuristic memory overcommit handling by estimating the amount of memory available and failing requests that are blatantly invalid. Unfortunately, since memory is allocated using a heuristic rather than a precise algorithm, this setting can sometimes allow available memory on the system to be overloaded.
- **1** — The kernel performs no memory overcommit handling. Under this setting, the potential for memory overload is increased, but so is performance for memory-intensive tasks.
- **2** — The kernel denies requests for memory equal to or larger than the sum of total available swap and the percentage of physical RAM specified in ***overcommit_ratio***. This setting is best if you want a lesser risk of memory overcommitment.

Note

This setting is only recommended for systems with swap areas larger than their physical memory.

overcommit_ratio

Specifies the percentage of physical RAM considered when ***overcommit_memory*** is set to **2**. The default value is **50**.

max_map_count

Defines the maximum number of memory map areas that a process may use. In most cases, the default value of **65530** is appropriate. Increase this value if your application needs to map more than this number of files.

nr_hugepages

Defines the number of hugepages configured in the kernel. The default value is 0. It is only possible to allocate (or deallocate) hugepages if there are sufficient physically contiguous free pages in the system. Pages reserved by this parameter cannot be used for other purposes. Further information is available from the installed documentation: **/usr/share/doc/kernel-doc-*kernel_version*/Documentation/vm/hugetlbpage.txt**

Capacity-related Kernel Tunables

Each of the following parameters is located under **/proc/sys/kernel/** in the proc file system.

msgmax

Defines the maximum allowable size in bytes of any single message in a message queue. This value must not exceed the size of the queue (***msgmnb***). The default value is **65536**.

msgmnb

Defines the maximum size in bytes of a single message queue. The default value is **65536** bytes.

msgmni

Defines the maximum number of message queue identifiers (and therefore the maximum number of queues). The default value on machines with 64-bit architecture is **1985**; for 32-bit architecture, the default value is **1736**.

shmall

Defines the total amount of shared memory in bytes that can be used on the system at one time. The default value for machines with 64-bit architecture is **4294967296**; for 32-bit architecture the default value is **268435456**.

shmmax

Defines the maximum shared memory segment allowed by the kernel, in bytes. The default value on machines with 64-bit architecture is **68719476736**; for 32-bit architecture, the default value is **4294967295**. Note, however, that the kernel supports values much larger than this.

shmmni

Defines the system-wide maximum number of shared memory segments. The default value is **4096** on both 64-bit and 32-bit architectures.

threads-max

Defines the system-wide maximum number of threads (tasks) to be used by the kernel at one time. The default value is equal to the kernel ***max_threads*** value. The formula in use is:

```
max_threads = mempages / (8 * THREAD_SIZE / PAGE_SIZE )
```

The minimum value of ***threads-max*** is **20**.

Capacity-related File System Tunables

Each of the following parameters is located under **/proc/sys/fs/** in the proc file system.

aio-max-nr

Defines the maximum allowed number of events in all active asynchronous I/O contexts. The default value is **65536**. Note that changing this value does not pre-allocate or resize any kernel data structures.

file-max

Lists the maximum number of file handles that the kernel allocates. The default value matches the value of ***files_stat.max_files*** in the kernel, which is set to the largest value out of either **(mempages * (PAGE_SIZE / 1024)) / 10**, or **NR_FILE** (8192 in Red Hat Enterprise Linux). Raising this value can resolve errors caused by a lack of available file handles.

Out-of-Memory Kill Tunables

Out of Memory (OOM) refers to a computing state where all available memory, including swap space, has been allocated. By default, this situation causes the system to panic and stop functioning as expected. However, setting the ***/proc/sys/vm/panic_on_oom*** parameter to **0** instructs the kernel to call the **oom_killer** function when OOM occurs. Usually, **oom_killer** can kill rogue processes and the system survives.

The following parameter can be set on a per-process basis, giving you increased control over which processes are killed by the **oom_killer** function. It is located under **/proc/*pid*/** in the proc file system, where ***pid*** is the process ID number.

oom_adj

Defines a value from **-16** to **15** that helps determine the ***oom_score*** of a process. The higher the ***oom_score*** value, the more likely the process will be killed by the **oom_killer**. Setting a ***oom_adj*** value of **-17** disables the **oom_killer** for that process.

Important

Any processes spawned by an adjusted process will inherit that process's ***oom_score***. For example, if an **sshd** process is protected from the **oom_killer** function, all processes initiated by that SSH session will also be protected. This can affect the **oom_killer** function's ability to salvage the system if OOM occurs.

5.5. Tuning Virtual Memory

Virtual memory is typically consumed by processes, file system caches, and the kernel. Virtual memory utilization depends on a number of factors, which can be affected by the following parameters:

swappiness

A value from 0 to 100 which controls the degree to which the system swaps. A high value

prioritizes system performance, aggressively swapping processes out of physical memory when they are not active. A low value prioritizes interactivity and avoids swapping processes out of physical memory for as long as possible, which decreases response latency. The default value is **60**.

min_free_kbytes

The minimum number of kilobytes to keep free across the system. This value is used to compute a watermark value for each low memory zone, which are then assigned a number of reserved free pages proportional to their size.

Extreme values can break your system

Be cautious when setting this parameter, as both too-low and too-high values can be damaging.
Setting ***min_free_kbytes*** too low prevents the system from reclaiming memory. This can result in system hangs and OOM-killing multiple processes.
However, setting this parameter to a value that is too high (5-10% of total system memory) will cause your system to become out-of-memory immediately. Linux is designed to use all available RAM to cache file system data. Setting a high ***min_free_kbytes*** value results in the system spending too much time reclaiming memory.

dirty_ratio

Defines a percentage value. Writeout of dirty data begins (via **pdflush**) when dirty data comprises this percentage of total system memory. The default value is **20**.

dirty_background_ratio

Defines a percentage value. Writeout of dirty data begins in the background (via **pdflush**) when dirty data comprises this percentage of total memory. The default value is **10**.

drop_caches

Setting this value to **1**, **2**, or **3** causes the kernel to drop various combinations of page cache and slab cache.

1

The system invalidates and frees all page cache memory.

2

The system frees all unused slab cache memory.

3

The system frees all page cache and slab cache memory.

This is a non-destructive operation. Since dirty objects cannot be freed, running **sync** before setting this parameter's value is recommended.

Important

Using the ***drop_caches*** to free memory is not recommended in a production environment.

To set these values temporarily during tuning, echo the desired value to the appropriate file in the proc file system. For example, to set ***swappiness*** temporarily to **50**, run:

```
# echo 50 > /proc/sys/vm/swappiness
```

To set this value persistently, you will need to use the **sysctl** command. For further information, refer to the *Deployment Guide*, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

Chapter 6. Input/Output

6.1. Features

Red Hat Enterprise Linux 6 introduces a number of performance enhancements in the I/O stack:

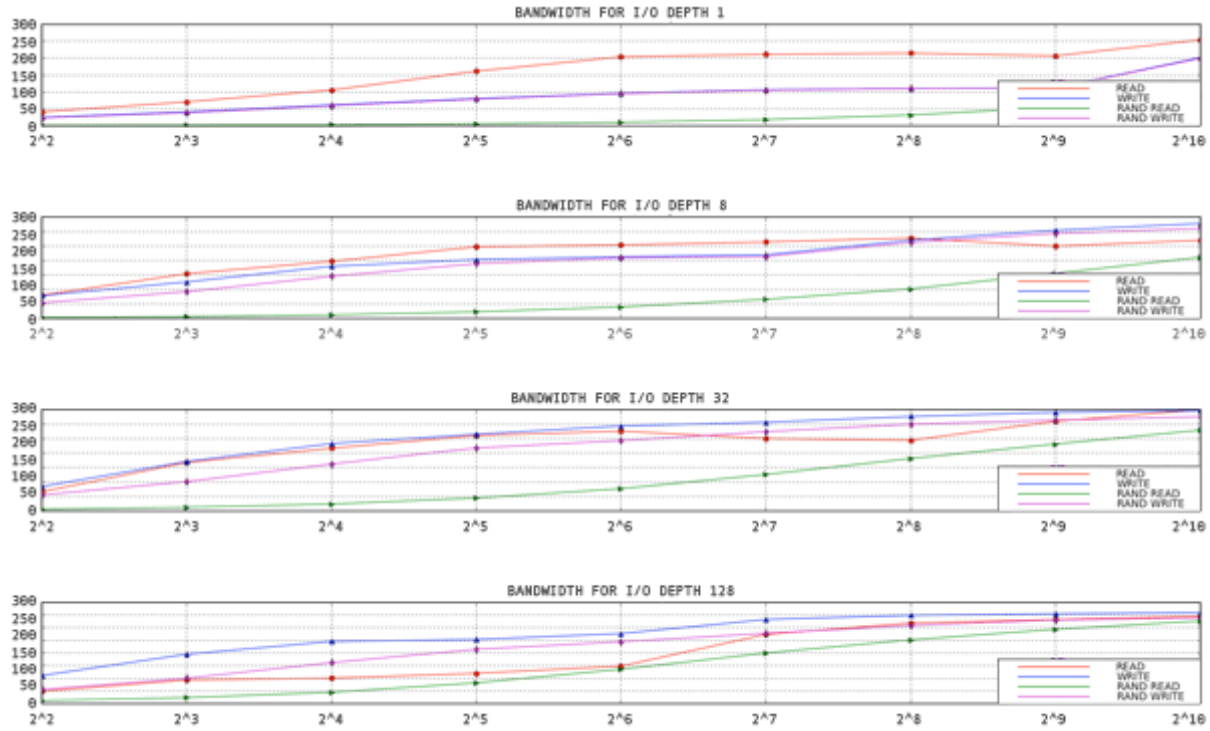
- Solid state disks (SSDs) are now recognized automatically, and the performance of the I/O scheduler is tuned to take advantage of the high I/Os per second (IOPS) that these devices can perform.
- Discard support has been added to the kernel to report unused block ranges to the underlying storage. This helps SSDs with their wear-leveling algorithms. It also helps storage that supports logical block provisioning (a sort of virtual address space for storage) by keeping closer tabs on the actual amount of storage in-use.
- The file system barrier implementation was overhauled in Red Hat Enterprise Linux 6.1 to make it more performant.
- **`pdflush`** has been replaced by per-backing-device flusher threads, which greatly improves system scalability on configurations with large LUN counts.

6.2. Analysis

Successfully tuning storage stack performance requires an understanding of how data flows through the system, as well as intimate knowledge of the underlying storage and how it performs under varying workloads. It also requires an understanding of the actual workload being tuned.

Whenever you deploy a new system, it is a good idea to profile the storage from the bottom up. Start with the raw LUNs or disks, and evaluate their performance using direct I/O (I/O which bypasses the kernel's page cache). This is the most basic test you can perform, and will be the standard by which you measure I/O performance in the stack. Start with a basic workload generator (such as **aio-stress**) that produces sequential and random reads and writes across a variety of I/O sizes and queue depths.

Following is a graph from a series of **aio-stress** runs, each of which performs four stages: sequential write, sequential read, random write and random read. In this example, the tool is configured to run across a range of record sizes (the x axis) and queue depths (one per graph). The queue depth represents the total number of I/O operations in progress at a given time.



The y-axis shows the bandwidth in megabytes per second. The x-axis shows the I/O Size in kilobytes.

Figure 6.1. aio-stress output for 1 thread, 1 file

Notice how the throughput line trends from the lower left corner to the upper right. Also note that, for a given record size, you can get more throughput from the storage by increasing the number of I/Os in progress.

By running these simple workloads against your storage, you will gain an understanding of how your storage performs under load. Retain the data generated by these tests for comparison when analyzing more complex workloads.

If you will be using device mapper or md, add that layer in next and repeat your tests. If there is a large loss in performance, ensure that it is expected, or can be explained. For example, a performance drop may be expected if a checksumming raid layer has been added to the stack. Unexpected performance drops can be caused by misaligned I/O operations. By default, Red Hat Enterprise Linux aligns partitions and device mapper metadata optimally. However, not all types of storage report their optimal alignment, and so may require manual tuning.

After adding the device mapper or md layer, add a file system on top of the block device and test against that, still using direct I/O. Again, compare results to the prior tests and ensure that you understand any discrepancies. Direct-write I/O typically performs better on pre-allocated files, so ensure that you pre-allocate files before testing for performance.

Synthetic workload generators that you may find useful include:

- **aio-stress**
- **iozone**
- **fio**

6.3. Tools

There are a number of tools available to help diagnose performance problems in the I/O subsystem. **vmstat** provides a coarse overview of system performance. The following columns are most relevant to I/O: ***si*** (swap in), ***so*** (swap out), ***bi*** (block in), ***bo*** (block out), and ***wa*** (I/O wait time). ***si*** and ***so*** are useful when your swap space is on the same device as your data partition, and as an indicator of overall memory pressure. ***si*** and ***bi*** are read operations, while ***so*** and ***bo*** are write operations. Each of these categories is reported in kilobytes. ***wa*** is idle time; it indicates what portion of the run queue is blocked waiting for I/O complete.

Analyzing your system with **vmstat** will give you an idea of whether or not the I/O subsystem may be responsible for any performance issues. The ***free***, ***buff***, and ***cache*** columns are also worth noting. The ***cache*** value increasing alongside the ***bo*** value, followed by a drop in ***cache*** and an increase in ***free*** indicates that the system is performing write-back and invalidation of the page cache.

Note that the I/O numbers reported by **vmstat** are aggregations of all I/O to all devices. Once you have determined that there may be a performance gap in the I/O subsystem, you can examine the problem more closely with **iostat**, which will break down the I/O reporting by device. You can also retrieve more detailed information, such as the average request size, the number of reads and writes per second, and the amount of I/O merging going on.

Using the average request size and the average queue size (**avgqu-sz**), you can make some estimations about how the storage should perform using the graphs you generated when characterizing the performance of your storage. Some generalizations apply: for example, if the average request size is 4KB and the average queue size is 1, throughput is unlikely to be extremely performant.

If the performance numbers do not map to the performance you expect, you can perform more fine-grained analysis with **blktrace**. The **blktrace** suite of utilities gives fine-grained information on how much time is spent in the I/O subsystem. The output from **blktrace** is a set of binary trace files that can be post-processed by other utilities such as **blkparse**.

blkparse is the companion utility to **blktrace**. It reads the raw output from the trace and produces a short-hand textual version.

The following is an example of **blktrace** output:

```
8,64   3        1     0.000000000  4162  Q  RM 73992 + 8 [fs_mark]
8,64   3        0     0.000012707     0  m   N cfq4162S / alloced
8,64   3        2     0.000013433  4162  G  RM 73992 + 8 [fs_mark]
8,64   3        3     0.000015813  4162  P   N [fs_mark]
8,64   3        4     0.000017347  4162  I   R 73992 + 8 [fs_mark]
8,64   3        0     0.000018632     0  m   N cfq4162S / insert_request
8,64   3        0     0.000019655     0  m   N cfq4162S / add_to_rr
8,64   3        0     0.000021945     0  m   N cfq4162S / idle=0
8,64   3        5     0.000023460  4162  U   N [fs_mark] 1
8,64   3        0     0.000025761     0  m   N cfq workload slice:300
8,64   3        0     0.000027137     0  m   N cfq4162S / set_active wl_prio:0
wl_type:2
8,64   3        0     0.000028588     0  m   N cfq4162S / fifo=(null)
8,64   3        0     0.000029468     0  m   N cfq4162S / dispatch_insert
8,64   3        0     0.000031359     0  m   N cfq4162S / dispatched a request
8,64   3        0     0.000032306     0  m   N cfq4162S / activate rq, drv=1
8,64   3        6     0.000032735  4162  D   R 73992 + 8 [fs_mark]
8,64   1        1     0.004276637     0  C   R 73992 + 8 [0]
```

As you can see, the output is dense and difficult to read. You can tell which processes are responsible

for issuing I/O to your device, which is useful, but **blkparse** can give you additional information in an easy-to-digest format in its summary. **blkparse** summary information is printed at the very end of its output:

```
Total (sde):
Reads Queued:          19,       76KiB  Writes Queued:     142,183,  568,732KiB
Read Dispatches:       19,       76KiB  Write Dispatches:   25,440,  568,732KiB
Reads Requeued:         0               Writes Requeued:       125
Reads Completed:       19,       76KiB  Writes Completed:   25,315,  568,732KiB
Read Merges:            0,        0KiB  Write Merges:      116,868,  467,472KiB
IO unplugs:        20,087               Timer unplugs:           0
```

The summary shows average I/O rates, merging activity, and compares the read workload with the write workload. For the most part, however, **blkparse** output is too voluminous to be useful on its own. Fortunately, there are several tools to assist in visualizing the data.

btt provides an analysis of the amount of time the I/O spent in the different areas of the I/O stack. These areas are:

- Q — A block I/O is Queued
- G — Get Request

  A newly queued block I/O was not a candidate for merging with any existing request, so a new block layer request is allocated.
- M — A block I/O is Merged with an existing request.
- I — A request is Inserted into the device's queue.
- D — A request is issued to the Device.
- C — A request is Completed by the driver.
- P — The block device queue is Plugged, to allow the aggregation of requests.
- U — The device queue is Unplugged, allowing the aggregated requests to be issued to the device.

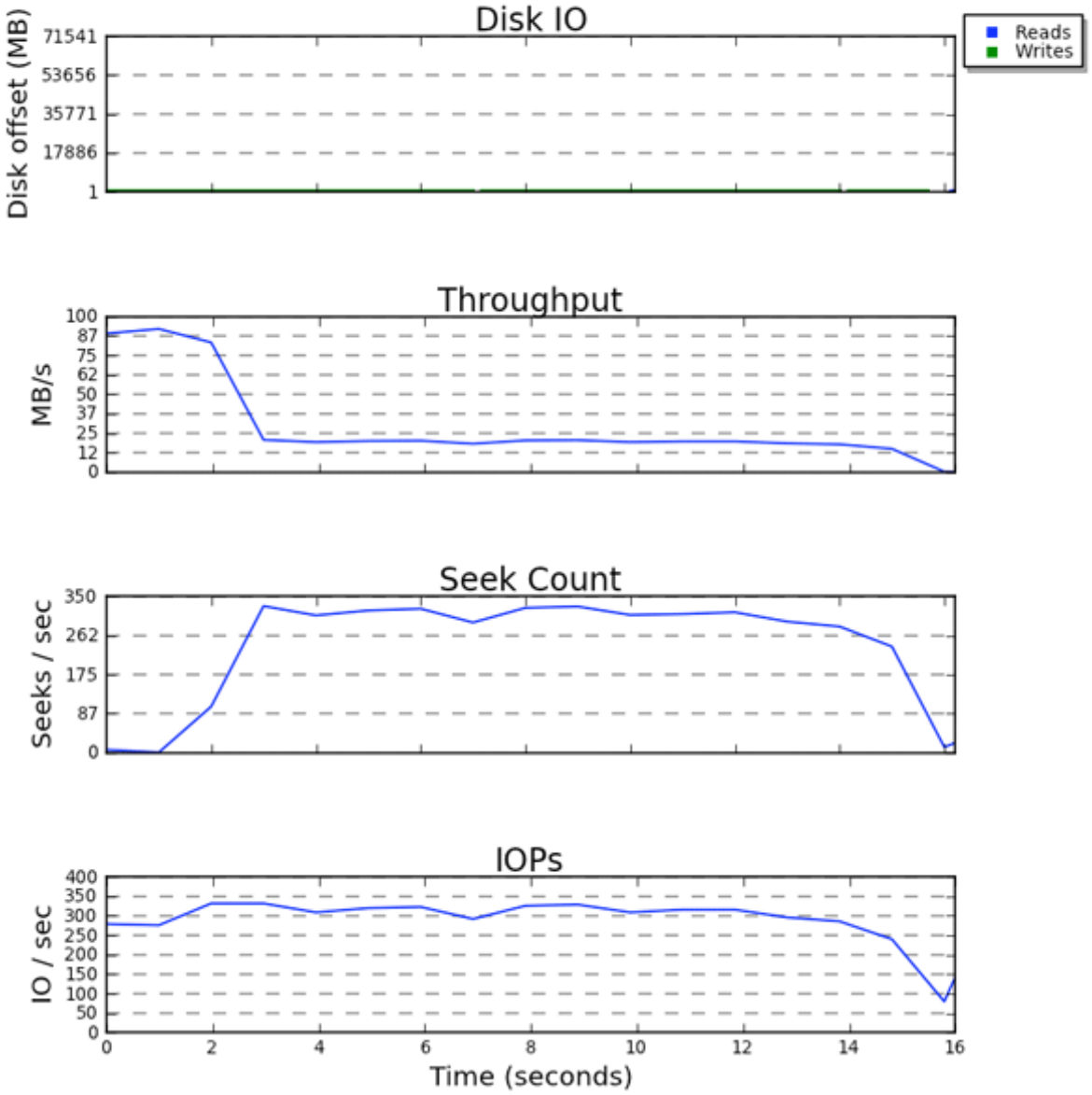
btt breaks down the time spent in each of these areas, as well as the time spent transitioning between them, like so:

- Q2Q — time between requests sent to the block layer
- Q2G — how long it takes from the time a block I/O is queued to the time it gets a request allocated for it
- G2I — how long it takes from the time a request is allocated to the time it is Inserted into the device's queue
- Q2M — how long it takes from the time a block I/O is queued to the time it gets merged with an existing request
- I2D — how long it takes from the time a request is inserted into the device's queue to the time it is actually issued to the device
- M2D — how long it takes from the time a block I/O is merged with an exiting request until the request is issued to the device
- D2C — service time of the request by the device
- Q2C — total time spent in the block layer for a request

You can deduce a lot about a workload from the above table. For example, if Q2Q is much larger than Q2C, that means the application is not issuing I/O in rapid succession. Thus, any performance problems you have may not be at all related to the I/O subsystem. If D2C is very high, then the device is taking a long time to service requests. This can indicate that the device is simply overloaded (which may be due to the fact that it is a shared resource), or it could be because the workload sent down to the device is

sub-optimal. If Q2G is very high, it means that there are a lot of requests queued concurrently. This could indicate that the storage is unable to keep up with the I/O load.

Finally, **seekwatcher** consumes **blktrace** binary data and generates a set of plots, including Logical Block Address (LBA), throughput, seeks per second, and I/Os Per Second (IOPS).



Avg Seeks/s	Avg MB/s	Avg IO/s	Run time (s)
252.57	31.72	305.99	16.21

Figure 6.2. Example seekwatcher output

All plots use time as the X axis. The LBA plot shows reads and writes in different colors. It is interesting to note the relationship between the throughput and seeks/sec graphs. For storage that is seek-sensitive, there is an inverse relation between the two plots. The IOPS graph is useful if, for example,

you are not getting the throughput you expect from a device, but you are hitting its IOPS limitations.

6.4. Configuration

One of the first decisions you will need to make is which I/O scheduler to use. This section provides an overview of each of the main schedulers to help you decide which is best for your workload.

6.4.1. Completely Fair Queuing (CFQ)

CFQ attempts to provide some fairness in I/O scheduling decisions based on the process which initiated the I/O. Three different scheduling classes are provided: real-time (RT), best-effort (BE), and idle. A scheduling class can be manually assigned to a process with the **`ionice`** command, or programmatically assigned via the **`ioprio_set`** system call. By default, processes are placed in the best-effort scheduling class. The real-time and best-effort scheduling classes are further subdivided into eight I/O priorities within each class, priority 0 being the highest and 7 the lowest. Processes in the real-time scheduling class are scheduled much more aggressively than processes in either best-effort or idle, so any scheduled real-time I/O is always performed before best-effort or idle I/O. This means that real-time priority I/O can starve out both the best-effort and idle classes. Best effort scheduling is the default scheduling class, and 4 is the default priority within this class. Processes in the idle scheduling class are only serviced when there is no other I/O pending in the system. Thus, it is very important to only set the I/O scheduling class of a process to idle if I/O from the process is not at all required for making forward progress.

CFQ provides fairness by assigning a time slice to each of the processes performing I/O. During its time slice, a process may have (by default) up to 8 requests in flight at a time. The scheduler tries to anticipate whether an application will issue more I/O in the near future based on historical data. If it is expected that a process will issue more I/O, then CFQ will idle, waiting for that I/O, even if there is I/O from other processes waiting to be issued.

Because of the idling performed by CFQ, it is often not a good fit for hardware that does not suffer from a large seek penalty, such as fast external storage arrays or solid state disks. If using CFQ on such storage is a requirement (for example, if you would also like to use the cgroup proportional weight I/O scheduler), you will need to tune some settings to improve CFQ performance. Set the following parameters in the files of the same name located in **`/sys/block/`*`device`*`/queue/iosched/`**:

```
slice_idle = 0
quantum = 64
group_idle = 1
```

When ***`group_idle`*** is set to 1, there is still the potential for I/O stalls (whereby the back-end storage is not busy due to idling). However, these stalls will be less frequent than idling on every queue in the system.

CFQ is a non-work-conserving I/O scheduler, which means it can be idle even when there are requests pending (as we discussed above). The stacking of non-work-conserving schedulers can introduce large latencies in the I/O path. An example of such stacking is using CFQ on top of a host-based hardware RAID controller. The RAID controller may implement its own non-work-conserving scheduler, thus causing delays at two levels in the stack. Non-work-conserving schedulers operate best when they have as much data as possible to base their decisions on. In the case of stacking such scheduling algorithms, the bottom-most scheduler will only see what the upper scheduler sends down. Thus, the lower layer will see an I/O pattern that is not at all representative of the actual workload.

Tunables

back_seek_max

Backward seeks are typically bad for performance, as they can incur greater delays in repositioning the heads than forward seeks do. However, CFQ will still perform them, if they are small enough. This tunable controls the maximum distance in KB the I/O scheduler will allow backward seeks. The default is **16** KB.

back_seek_penalty

Because of the inefficiency of backward seeks, a penalty is associated with each one. The penalty is a multiplier; for example, consider a disk head position at 1024KB. Assume there are two requests in the queue, one at 1008KB and another at 1040KB. The two requests are equidistant from the current head position. However, after applying the back seek penalty (default: 2), the request at the later position on disk is now twice as close as the earlier request. Thus, the head will move forward.

fifo_expire_async

This tunable controls how long an async (buffered write) request can go unserviced. After the expiration time (in milliseconds), a single starved async request will be moved to the dispatch list. The default is **250** ms.

fifo_expire_sync

This is the same as the fifo_expire_async tunable, for for synchronous (read and O_DIRECT write) requests. The default is **125** ms.

group_idle

When set, CFQ will idle on the last process issuing I/O in a cgroup. This should be set to **1** when using proportional weight I/O cgroups and setting ***slice_idle*** to **0** (typically done on fast storage).

group_isolation

If group isolation is enabled (set to **1**), it provides a stronger isolation between groups at the expense of throughput. Generally speaking, if group isolation is disabled, fairness is provided for sequential workloads only. Enabling group isolation provides fairness for both sequential and random workloads. The default value is **0** (disabled). Refer to **Documentation/cgroups/blkio-controller.txt** for further information.

low_latency

When low latency is enabled (set to **1**), CFQ attempts to provide a maximum wait time of 300 ms for each process issuing I/O on a device. This favors fairness over throughput. Disabling low latency (setting it to **0**) ignores target latency, allowing each process in the system to get a full time slice. Low latency is enabled by default.

quantum

The quantum controls the number of I/Os that CFQ will send to the storage at a time, essentially limiting the device queue depth. By default, this is set to **8**. The storage may support much deeper queue depths, but increasing ***quantum*** will also have a negative impact on latency, especially in the presence of large sequential write workloads.

slice_async

This tunable controls the time slice allotted to each process issuing asynchronous (buffered write) I/O. By default it is set to **40** ms.

slice_idle

This specifies how long CFQ should idle while waiting for further requests. The default value in Red Hat Enterprise Linux 6.1 and earlier is **8** ms. In Red Hat Enterprise Linux 6.2 and later, the default value is **0**. The zero value improves the throughput of external RAID storage by removing all idling at the queue and service tree level. However, a zero value can degrade throughput on internal non-RAID storage, because it increases the overall number of seeks. For non-RAID storage, we recommend a ***slice_idle*** value that is greater than 0.

slice_sync

This tunable dictates the time slice allotted to a process issuing synchronous (read or direct write) I/O. The default is **100** ms.

6.4.2. Deadline I/O Scheduler

The deadline I/O scheduler attempts to provide a guaranteed latency for requests. It is important to note that the latency measurement only starts when the requests gets down to the I/O scheduler (this is an important distinction, as an application may be put to sleep waiting for request descriptors to be freed). By default, reads are given priority over writes, since applications are more likely to block on read I/O.

Deadline dispatches I/Os in batches. A batch is a sequence of either read or write I/Os which are in increasing LBA order (the one-way elevator). After processing each batch, the I/O scheduler checks to see whether write requests have been starved for too long, and then decides whether to start a new batch of reads or writes. The FIFO list of requests is only checked for expired requests at the start of each batch, and then only for the data direction of that batch. So, if a write batch is selected, and there is an expired read request, that read request will not get serviced until the write batch completes.

Tunables

fifo_batch

This determines the number of reads or writes to issue in a single batch. The default is **16**. Setting this to a higher value may result in better throughput, but will also increase latency.

front_merges

You can set this tunable to **0** if you know your workload will never generate front merges. Unless you have measured the overhead of this check, it is advisable to leave it at its default setting (**1**).

read_expire

This tunable allows you to set the number of milliseconds in which a read request should be serviced. By default, this is set to **500** ms (half a second).

write_expire

This tunable allows you to set the number of milliseconds in which a write request should be

serviced. By default, this is set to **5000** ms (five seconds).

writes_starved

This tunable controls how many read batches can be processed before processing a single write batch. The higher this is set, the more preference is given to reads.

6.4.3. Noop

The Noop I/O scheduler implements a simple first-in first-out (FIFO) scheduling algorithm. Merging of requests happens at the generic block layer, but is a simple last-hit cache. If a system is CPU-bound and the storage is fast, this can be the best I/O scheduler to use.

Following are the tunables available for the block layer.

/sys/block/sdX/queue tunables

add_random

In some cases, the overhead of I/O events contributing to the entropy pool for **/dev/random** is measurable. In such cases, it may be desirable to set this value to 0.

max_sectors_kb

By default, the maximum request size sent to disk is **512** KB. This tunable can be used to either raise or lower that value. The minimum value is limited by the logical block size; the maximum value is limited by ***max_hw_sectors_kb***. There are some SSDs which perform worse when I/O sizes exceed the internal erase block size. In such cases, it is recommended to tune ***max_hw_sectors_kb*** down to the erase block size. You can test for this using an I/O generator such as **iozone** or **aio-stress**, varying the record size from, for example, **512** bytes to **1** MB.

nomerges

This tunable is primarily a debugging aid. Most workloads benefit from request merging (even on faster storage such as SSDs). In some cases, however, it is desirable to disable merging, such as when you want to see how many IOPS a storage back-end can process without disabling read-ahead or performing random I/O.

nr_requests

Each request queue has a limit on the total number of request descriptors that can be allocated for each of read and write I/Os. By default, the number is **128**, meaning 128 reads and 128 writes can be queued at a time before putting a process to sleep. The process put to sleep is the next to try to allocate a request, not necessarily the process that has allocated all of the available requests.

If you have a latency-sensitive application, then you should consider lowering the value of ***nr_requests*** in your request queue and limiting the command queue depth on the storage to a low number (even as low as **1**), so that writeback I/O cannot allocate all of the available request descriptors and fill up the device queue with write I/O. Once ***nr_requests*** have been allocated, all other processes attempting to perform I/O will be put to sleep to wait for requests to become available. This makes things more fair, as the requests are then distributed in a round-robin fashion (instead of letting one process consume them all in rapid succession). Note that this is only a problem when using the deadline or noop schedulers, as the default CFQ configuration

protects against this situation.

optimal_io_size

In some circumstances, the underlying storage will report an optimal I/O size. This is most common in hardware and software RAID, where the optimal I/O size is the stripe size. If this value is reported, applications should issue I/O aligned to and in multiples of the optimal I/O size whenever possible.

read_ahead_kb

The operating system can detect when an application is reading data sequentially from a file or from disk. In such cases, it performs an intelligent read-ahead algorithm, whereby more data than is requested by the user is read from disk. Thus, when the user next attempts to read a block of data, it will already by in the operating system's page cache. The potential down side to this is that the operating system can read more data from disk than necessary, which occupies space in the page cache until it is evicted because of high memory pressure. Having multiple processes doing false read-ahead would increase memory pressure in this circumstance.

For device mapper devices, it is often a good idea to increase the value of ***read_ahead_kb*** to a large number, such as **8192**. The reason is that a device mapper device is often made up of multiple underlying devices. Setting this value to the default (**128** KB) multiplied by the number of devices you are mapping is a good starting point for tuning.

rotational

Traditional hard disks have been rotational (made up of spinning platters). SSDs, however, are not. Most SSDs will advertise this properly. If, however, you come across a device that does not advertise this flag properly, it may be necessary to set rotational to **0** manually; when rotational is disabled, the I/O elevator does not use logic that is meant to reduce seeks, since there is little penalty for seek operations on non-rotational media.

rq_affinity

I/O completions can be processed on a different CPU from the one that issued the I/O. Setting ***rq_affinity*** to **1** causes the kernel to deliver completions to the CPU on which the I/O was issued. This can improve CPU data caching effectiveness.

Chapter 7. File Systems

Read this chapter for an overview of the file systems supported for use with Red Hat Enterprise Linux, and how to optimize their performance.

7.1. Tuning Considerations for File Systems

There are several tuning considerations common to all file systems: formatting and mount options selected on your system, and actions available to applications that can improve their performance on a given system.

7.1.1. Formatting Options

File system block size

Block size can be selected at **mkfs** time. The range of valid sizes depends on the system: the upper limit is the maximum page size of the host system, while the lower limit depends on the file system used. The default block size is appropriate for most use cases.

If you expect to create many files smaller than the default block size, you can set a smaller block size to minimize the amount of space wasted on disk. Note, however, that setting a smaller block size may limit the maximum size of the file system, and can cause additional runtime overhead, particularly for files greater than the selected block size.

File system geometry

If your system uses striped storage such as RAID5, you can improve performance by aligning data and metadata with the underlying storage geometry at **mkfs** time. For software RAID (LVM or MD) and some enterprise hardware storage, this information is queried and set automatically, but in many cases the administrator must specify this geometry manually with **mkfs** at the command line.

Refer to the *Storage Administration Guide* for further information about creating and maintaining these file systems.

External journals

Metadata-intensive workloads mean that the log section of a journaling file system (such as ext4 and XFS) is updated extremely frequently. To minimize seek time from file system to journal, you can place the journal on dedicated storage. Note, however, that placing the journal on external storage that is slower than the primary file system can nullify any potential advantage associated with using external storage.

Warning

Ensure that your external journal is reliable. The loss of an external journal device will cause file system corruption.

External journals are created at **mkfs** time, with journal devices being specified at mount time. Refer to the **mke2fs(8)**, **mkfs.xfs(8)**, and **mount(8)** man pages for further information.

7.1.2. Mount Options

Barriers

A write barrier is a kernel mechanism used to ensure that file system metadata is correctly written and ordered on persistent storage, even when storage devices with volatile write caches lose power. File systems with write barriers enabled also ensure that any data transmitted via **fsync()** persists across a power outage. Red Hat Enterprise Linux enables barriers by default on all hardware that supports them.

However, enabling write barriers slows some applications significantly; specifically, applications that use **fsync()** heavily, or create and delete many small files. For storage with no volatile write cache, or in the rare case where file system inconsistencies and data loss after a power loss is acceptable, barriers can be disabled by using the ***nobarrier*** mount option. For further information, refer to the *Storage Administration Guide*.

Access Time (noatime)

Historically, when a file is read, the access time (***atime***) for that file must be updated in the inode metadata, which involves additional write I/O. If accurate ***atime*** metadata is not required, mount the file system with the ***noatime*** option to eliminate these metadata updates. In most cases, however, ***atime*** is not a large overhead due to the default relative atime (or ***relatime***) behavior in the Red Hat Enterprise Linux 6 kernel. The ***relatime*** behavior only updates ***atime*** if the previous ***atime*** is older than the modification time (***mtime***) or status change time (***ctime***).

Note

Enabling the ***noatime*** option also enables ***nodiratime*** behavior; there is no need to set both ***noatime*** and ***nodiratime***.

Increased read-ahead support

Read-ahead speeds up file access by pre-fetching data and loading it into the page cache so that it can be available earlier in memory instead of from disk. Some workloads, such as those involving heavy streaming of sequential I/O, benefit from high read-ahead values.

The **tuned** tool and the use of LVM striping elevate the read-ahead value, but this is not always sufficient for some workloads. Additionally, Red Hat Enterprise Linux is not always able to set an appropriate read-ahead value based on what it can detect of your file system. For example, if a powerful storage array presents itself to Red Hat Enterprise Linux as a single powerful LUN, the operating system will not treat it as a powerful LUN array, and therefore will not by default make full use of the read-ahead advantages potentially available to the storage.

Use the **blockdev** command to view and edit the read-ahead value. To view the current read-ahead value for a particular block device, run:

```
# blockdev -getra device
```

To modify the read-ahead value for that block device, run the following command. ***N*** represents the number of 512-byte sectors.

```
# blockdev -setra N device
```

Note that the value selected with the **blockdev** command will not persist between boots. We recommend creating a run level **init.d** script to set this value during boot.

7.1.3. File system maintenance

Discard unused blocks

Batch discard and online discard operations are features of mounted file systems that discard blocks which are not in use by the file system. These operations are useful for both solid-state drives and thinly-provisioned storage.

Batch discard operations are run explicitly by the user with the **fstrim** command. This command discards all unused blocks in a file system that match the user's criteria. Both operation types are supported for use with the XFS and ext4 file systems in Red Hat Enterprise Linux 6.2 and later as long as the block device underlying the file system supports physical discard operations. Physical discard operations are supported if the value of **/sys/block/*device*/queue/discard_max_bytes** is not zero.

Online discard operations are specified at mount time with the **-o discard** option (either in **/etc/fstab** or as part of the **mount** command), and run in realtime without user intervention. Online discard operations only discard blocks that are transitioning from used to free. Online discard operations are supported on ext4 file systems in Red Hat Enterprise Linux 6.2 and later, and on XFS file systems in Red Hat Enterprise Linux 6.4 and later.

Red Hat recommends batch discard operations unless the system's workload is such that batch discard is not feasible, or online discard operations are necessary to maintain performance.

7.1.4. Application Considerations

Pre-allocation

The ext4, XFS, and GFS2 file systems support efficient space pre-allocation via the **fallocate(2)** glibc call. In cases where files may otherwise become badly fragmented due to write patterns, leading to poor read performance, space preallocation can be a useful technique. Pre-allocation marks disk space as if it has been allocated to a file, without writing any data into that space. Until real data is written to a pre-allocated block, read operations will return zeroes.

7.2. Profiles for file system performance

The **tuned-adm** tool allows users to easily swap between a number of profiles that have been designed to enhance performance for specific use cases. The profiles that are particularly useful in improving storage performance are:

latency-performance

A server profile for typical latency performance tuning. It disables **tuned** and **ktune** power-saving mechanisms. The **cpuspeed** mode changes to **performance**. The I/O elevator is changed to **deadline** for each device. The ***cpu_dma_latency*** parameter is registered with a value of **0** (the lowest possible latency) for power management quality-of-service to limit latency where possible.

throughput-performance

A server profile for typical throughput performance tuning. This profile is recommended if the system does not have enterprise-class storage. It is the same as **latency-performance**, except:

- ***kernel.sched_min_granularity_ns*** (scheduler minimal preemption granularity) is set to

10 milliseconds,

- ***kernel.sched_wakeup_granularity_ns*** (scheduler wake-up granularity) is set to **15** milliseconds,
- ***vm.dirty_ratio*** (virtual machine dirty ratio) is set to 40%, and
- transparent huge pages are enabled.

enterprise-storage

This profile is recommended for enterprise-sized server configurations with enterprise-class storage, including battery-backed controller cache protection and management of on-disk cache. It is the same as the **throughput-performance** profile, except:

- ***readahead*** value is set to **4x**, and
- non root/boot file systems are re-mounted with **barrier=0**.

More information about **tuned-adm** is available on the man page (**man tuned-adm**), or in the *Power Management Guide* available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

7.3. File Systems

7.3.1. The Ext4 File System

The ext4 file system is a scalable extension of the default ext3 file system available in Red Hat Enterprise Linux 5. Ext4 is now the default file system for Red Hat Enterprise Linux 6, and is supported for a maximum file system size of 16 TB and a single file maximum size of 16TB. It also removes the 32000 sub-directory limit present in ext3.

Note

For file systems larger than 16TB, we recommend using a scalable high capacity file system such as XFS. For further information, see Section 7.3.2, “The XFS File System”.

The ext4 file system defaults are optimal for most workloads, but if performance analysis shows that file system behavior is impacting performance, several tuning options are available:

Inode table initialization

For very large file systems, the **mkfs.ext4** process can take a very long time to initialize all inode tables in the file system. This process can be deferred with the ***-E lazy_itable_init=1*** option. If this is used, kernel processes will continue to initialize the file system after it is mounted. The rate at which this initialization occurs can be controlled with the ***-o init_itable=n*** option for the **mount** command, where the amount of time spent performing this background initialization is roughly 1/n. The default value for **n** is **10**.

Auto-fsync behavior

Because some applications do not always properly **fsync()** after renaming an existing file, or truncating and rewriting, ext4 defaults to automatic syncing of files after replace-via-rename and replace-via-truncate operations. This behavior is largely consistent with older ext3 filesystem

behavior. However, **fsync()** operations can be time consuming, so if this automatic behavior is not required, use the ***-o noauto_da_alloc*** option with the **mount** command to disable it. This will mean that the application must explicitly use **fsync()** to ensure data persistence.

Journal I/O priority

By default, journal commit I/O is given a slightly higher priority than normal I/O. This priority can be controlled with the ***journal_iopriio=n*** option of the **mount** command. The default value is **3**. Valid values range from 0 to 7, with 0 being the highest priority I/O.

For other **mkfs** and tuning options, please see the **mkfs.ext4(8)** and **mount(8)** man pages, as well as the **Documentation/filesystems/ext4.txt** file in the *kernel-doc* package.

7.3.2. The XFS File System

XFS is a robust and highly-scalable single host 64-bit journaling file system. It is entirely extent-based, so it supports very large file and file system sizes. The maximum supported file system size is 500 TB. The number of files an XFS system can hold is limited only by the space available in the file system.

XFS supports metadata journaling, which facilitates quicker crash recovery. The XFS file system can also be defragmented and enlarged while mounted and active. In addition, Red Hat Enterprise Linux 6 supports backup and restore utilities specific to XFS.

XFS uses extent-based allocation, and features a number of allocation schemes such as delayed allocation and explicit pre-allocation. Extent-based allocation provides a more compact and efficient method of tracking used space in a file system, and improves large file performance by reducing fragmentation and the space consumed by metadata. Delayed allocation improves the chance that a file will be written in a contiguous group of blocks, reducing fragmentation and improving performance. Pre-allocation can be used to prevent fragmentation entirely in cases where the application knows the amount of data it needs to write ahead of time.

XFS provides excellent I/O scalability by using b-trees to index all user data and metadata. Object counts grow as all operations on indexes inherit the logarithmic scalability characteristics of the underlying b-trees. Some of the tuning options XFS provides at **mkfs** time vary the width of the b-trees, which changes the scalability characteristics of different subsystems.

7.3.2.1. Basic tuning for XFS

In general, the default XFS format and mount options are optimal for most workloads; Red Hat recommends that the default values are used unless specific configuration changes are expected to benefit the workload of the file system. If software RAID is in use, the **mkfs.xfs** command automatically configures itself with the correct stripe unit and width to align with the hardware. This may need to be manually configured if hardware RAID is in use.

The **inode64** mount option is highly recommended for multi-terabyte file systems, except where the file system is exported via NFS and legacy 32-bit NFS clients require access to the file system.

The **logbsize** mount option is recommended for file systems that are modified frequently, or in bursts. The default value is **MAX** (32 KB, log stripe unit), and the maximum size is 256 KB. A value of 256 KB is recommended for file systems that undergo heavy modifications.

7.3.2.2. Advanced tuning for XFS

Before changing XFS parameters, you need to understand why the default XFS parameters are causing performance problems. This involves understanding what your application is doing, and how the file

system is reacting to those operations.

Observable performance problems that can be corrected or reduced by tuning are generally caused by file fragmentation or resource contention in the file system. There are different ways to address these problems, and in some cases fixing the problem will require that the application, rather than the file system configuration, be modified.

If you have not been through this process previously, it is recommended that you engage your local Red Hat support engineer for advice.

7.3.2.2.1. Optimizing for a large number of files

XFS imposes an arbitrary limit on the number of files that a file system can hold. In general, this limit is high enough that it will never be hit. If you know that the default limit will be insufficient ahead of time, you can increase the percentage of file system space allowed for inodes with the **mkfs.xfs** command. If you encounter the file limit after file system creation (usually indicated by ENOSPC errors when attempting to create a file or directory even though free space is available), you can adjust the limit with the **xfs_growfs** command.

7.3.2.2.2. Optimizing for a large number of files in a single directory

Directory block size is fixed for the life of a file system, and cannot be changed except upon initial formatting with **mkfs**. The minimum directory block is the file system block size, which defaults to **MAX** (4 KB, file system block size). In general, there is no reason to reduce the directory block size.

Because the directory structure is b-tree based, changing the block size affects the amount of directory information that can be retrieved or modified per physical I/O. The larger the directory becomes, the more I/O each operation requires at a given block size.

However, when larger directory block sizes are in use, more CPU is consumed by each modification operation compared to the same operation on a file system with a smaller directory block size. This means that for small directory sizes, large directory block sizes will result in lower modification performance. When the directory reaches a size where I/O is the performance-limiting factor, large block size directories perform better.

If writing to the file system is more common or more important than reading, such as in a file system that stores backups (where writing backups to the file system happens more frequently than restoring the backups):

- file systems requiring no more than 1–2 million directory entries (with entry name lengths of 20–40 bytes) perform best with the default configuration of 4 KB file system block size and 4 KB directory block size.
- file systems requiring between 1–10 million directory entries perform better with a larger block size of 16 KB
- file systems requiring more than 10 million directory entries perform better with an even larger block size of 64 KB

If reading from the file system is more common or more important than writing, for example, in a mirrored download server, the contents of which are viewed more often than modified, the number of entries to which these block sizes apply should be reduced by a factor of ten. For example, the default system and directory block size is best for read-heavy file systems with no more than ten to twenty thousand directory entries.

7.3.2.2.3. Optimising for concurrency

Unlike other file systems, XFS can perform many types of allocation and deallocation operations

concurrently provided that the operations are occurring on non-shared objects. Allocation or deallocation of extents can occur concurrently provided that the concurrent operations occur in different allocation groups. Similarly, allocation or deallocation of inodes can occur concurrently provided that the concurrent operations affect different allocation groups.

The number of allocation groups becomes important when using machines with a high CPU count and multi-threaded applications that attempt to perform operations concurrently. If only four allocation groups exist, then sustained, parallel metadata operations will only scale as far as those four CPUs (the concurrency limit provided by the system). For small file systems, ensure that the number of allocation groups is supported by the concurrency provided by the system. For large file systems (tens of terabytes and larger) the default formatting options generally create sufficient allocation groups to avoid limiting concurrency.

Applications must be aware of single points of contention in order to use the parallelism inherent in the structure of the XFS file system. It is not possible to modify a directory concurrently, so applications that create and remove large numbers of files should avoid storing all files in a single directory. Each directory created is placed in a different allocation group, so techniques such as hashing files over multiple sub-directories provide a more scalable storage pattern compared to using a single large directory.

7.3.2.2.4. Optimising for applications that use extended attributes

XFS can store small attributes directly in the inode if space is available in the inode. If the attribute fits into the inode, then it can be retrieved and modified without requiring extra I/O to retrieve separate attribute blocks. The performance differential between in-line and out-of-line attributes can easily be an order of magnitude slower for out-of-line attributes.

For the default inode size of 256 bytes, roughly 100 bytes of attribute space is available depending on the number of data extent pointers also stored in the inode. The default inode size is really only useful for storing a small number of small attributes.

Increasing the inode size at mkfs time can increase the amount of space available for storing attributes in-line. A 512 byte inode size increases the space available for attributes to roughly 350 bytes; a 2 KB inode has roughly 1900 bytes of space available.

There is, however, a limit on the size of the individual attributes that can be stored in-line - there is a maximum size limit of 254 bytes for both the attribute name and the value (that is, an attribute with a name length of 254 bytes and a value length of 254 bytes will stay in-line). Exceeding these size limits forces the attributes out of line, even if there would have been enough space to store all the attributes in the inode.

7.3.2.2.5. Optimising for sustained metadata modifications

The size of the log is the main factor in determining the achievable level of sustained metadata modification. The log device is circular, so before the tail can be overwritten all the modifications in the log must be written to the real locations on disk. This can involve a significant amount of seeking to write back all dirty metadata. The default configuration scales the log size in relation to the overall file system size, so in most cases log size will not require tuning.

A small log device will result in very frequent metadata writeback - the log will constantly be pushing on its tail to free up space and so frequently modified metadata will be frequently written to disk, causing operations to be slow.

Increasing the log size increases the time period between tail pushing events. This allows better aggregation of dirty metadata, resulting in better metadata writeback patterns, and less writeback of frequently modified metadata. The trade-off is that larger logs require more memory to track all

outstanding changes in memory.

If you have a machine with limited memory, then large logs are not beneficial because memory constraints will cause metadata writeback long before the benefits of a large log can be realised. In these cases, smaller rather than larger logs will often provide better performance because metadata writeback from the log running out of space is more efficient than writeback driven by memory reclamation.

You should always try to align the log to the underlying stripe unit of the device that contains the file system. **mkfs** does this by default for MD and DM devices, but for hardware RAID it may need to be specified. Setting this correctly avoids all possibility of log I/O causing unaligned I/O and subsequent read-modify-write operations when writing modifications to disk.

Log operation can be further improved by editing mount options. Increasing the size of the in-memory log buffers (**logbsize**) increases the speed at which changes can be written to the log. The default log buffer size is **MAX** (32 KB, log stripe unit), and the maximum size is 256 KB. In general, a larger value results in faster performance. However, under fsync-heavy workloads, small log buffers can be noticeably faster than large buffers with a large stripe unit alignment.

The **delaylog** mount option also improves sustained metadata modification performance by reducing the number of changes to the log. It achieves this by aggregating individual changes in memory before writing them to the log: frequently modified metadata is written to the log periodically instead of on every modification. This option increases the memory usage of tracking dirty metadata and increases the potential lost operations when a crash occurs, but can improve metadata modification speed and scalability by an order of magnitude or more. Use of this option does not reduce data or metadata integrity when **fsync**, **fdatasync** or **sync** are used to ensure data and metadata is written to disk.

7.4. Clustering

Clustered storage provides a consistent file system image across all servers in a cluster, allowing servers to read and write to a single, shared file system. This simplifies storage administration by limiting tasks like installing and patching applications to one file system. A cluster-wide file system also eliminates the need for redundant copies of application data, simplifying backup and disaster recovery.

Red Hat's High Availability Add-On provides clustered storage in conjunction with Red Hat Global File System 2 (part of the Resilient Storage Add-On).

7.4.1. Global File System 2

Global File System 2 (GFS2) is a native file system that interfaces directly with the Linux kernel file system. It allows multiple computers (nodes) to simultaneously share the same storage device in a cluster. The GFS2 file system is largely self-tuning, but manual tuning is possible. This section outlines performance considerations when attempting to tune performance manually.

As of Red Hat Enterprise Linux 6.5, GFS2 includes the Orlov block allocator. This allows administrators to spread out block allocations on disk, so that the contents of directories can be placed in proximity to the directories on disk. This generally increases write speed within those directories.

All directories created in the top-level directory of the GFS2 mount point are spaced automatically. To treat another directory as a top-level directory, mark that directory with the **T** attribute, like so.

```
chattr +T directory
```

This ensures that all subdirectories created in the marked directory are spaced on disk.

Red Hat Enterprise Linux 6.4 introduced improvements to file fragmentation management in GFS2. Files created by Red Hat Enterprise Linux 6.3 or earlier were prone to file fragmentation if multiple files were written at the same time by more than one process. This fragmentation made things run slowly, especially in workloads involving large files. With Red Hat Enterprise Linux 6.4, simultaneous writes result in less file fragmentation and therefore better performance for these workloads.

While there is no defragmentation tool for GFS2 on Red Hat Enterprise Linux, you can defragment individual files by identifying them with the **filefrag** tool, copying them to temporary files, and renaming the temporary files to replace the originals. (This procedure can also be done in versions prior to 6.4 as long as the writing is done sequentially.)

Since GFS2 uses a global locking mechanism that potentially requires communication between nodes of a cluster, the best performance will be achieved when your system is designed to avoid file and directory contention between these nodes. Some methods of avoiding contention are to:

- Pre-allocate files and directories with **fallocate** where possible, to optimize the allocation process and avoid the need to lock source pages.
- Minimize the areas of the file system that are shared between multiple nodes to minimize cross-node cache invalidation and improve performance. For example, if multiple nodes mount the same file system, but access different sub-directories, you will likely achieve better performance by moving one subdirectory to a separate file system.
- Select an optimal resource group size and number. This depends on typical file sizes and available free space on the system, and affects the likelihood that multiple nodes will attempt to use a resource group simultaneously. Too many resource groups can slow block allocation while allocation space is located, while too few resource groups can cause lock contention during deallocation. It is generally best to test multiple configurations to determine which is best for your workload.

However, contention is not the only issue that can affect GFS2 file system performance. Other best practices to improve overall performance are to:

- Select your storage hardware according to the expected I/O patterns from cluster nodes and the performance requirements of the file system.
- Use solid-state storage where possible to lower seek time.
- Create an appropriately-sized file system for your workload, and ensure that the file system is never at more than 80% capacity. Smaller file systems will have proportionally shorter backup times, and require less time and memory for file system checks, but are subject to high fragmentation if they are too small for their workload.
- Set larger journal sizes for metadata-intensive workloads, or when journaled data is in use. Although this uses more memory, it improves performance because more journaling space is available to store data before a write is necessary.
- Ensure that clocks on GFS2 nodes are synchronized to avoid issues with networked applications. We recommend using NTP (Network Time Protocol).
- Unless file or directory access times are critical to the operation of your application, mount the file system with the **noatime** and **nodiratime** mount options.

Note

Red Hat strongly recommends the use of the **noatime** option with GFS2.

- If you need to use quotas, try to reduce the frequency of quota synchronization transactions or use fuzzy quota synchronization to prevent performance issues arising from constant quota file updates.

Note

Fuzzy quota accounting can allow users and groups to slightly exceed their quota limit. To minimize this issue, GFS2 dynamically reduces the synchronization period as a user or group approaches its quota limit.

For more detailed information about each aspect of GFS2 performance tuning, refer to the *Global File System 2* guide, available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

Chapter 8. Networking

Over time, Red Hat Enterprise Linux's network stack has been upgraded with numerous automated optimization features. For most workloads, the auto-configured network settings provide optimized performance.

In most cases, networking performance problems are actually caused by a malfunction in hardware or faulty infrastructure. Such causes are beyond the scope of this document; the performance issues and solutions discussed in this chapter are useful in optimizing perfectly functional systems.

Networking is a delicate subsystem, containing different parts with sensitive connections. This is why the open source community and Red Hat invest much work in implementing ways to automatically optimize network performance. As such, given most workloads, you may never even need to reconfigure networking for performance.

8.1. Network Performance Enhancements

Red Hat Enterprise Linux 6.1 provided the following network performance enhancements:

Receive Packet Steering (RPS)

RPS enables a single NIC **rx** queue to have its receive **softirq** workload distributed among several CPUs. This helps prevent network traffic from being bottlenecked on a single NIC hardware queue.

To enable RPS, specify the target CPU names in **/sys/class/net/*ethX*/queues/*rx-N*/rps_cpus**, replacing ***ethX*** with the NIC's corresponding device name (for example, **eth1**, **eth2**) and ***rx-N*** with the specified NIC receive queue. This will allow the specified CPUs in the file to process data from queue ***rx-N*** on ***ethX***. When specifying CPUs, consider the queue's *cache affinity* [4].

Receive Flow Steering

RFS is an extension of RPS, allowing the administrator to configure a hash table that is populated automatically when applications receive data and are interrogated by the network stack. This determines which applications are receiving each piece of network data (based on source:destination network information).

Using this information, the network stack can schedule the most optimal CPU to receive each packet. To configure RFS, use the following tunables:

/proc/sys/net/core/rps_sock_flow_entries

This controls the maximum number of sockets/flows that the kernel can steer towards any specified CPU. This is a system-wide, shared limit.

/sys/class/net/*ethX*/queues/*rx-N*/rps_flow_cnt

This controls the maximum number of sockets/flows that the kernel can steer for a specified receive queue (***rx-N***) on a NIC (***ethX***). Note that sum of all per-queue values for this tunable on all NICs should be equal or less than that of **/proc/sys/net/core/rps_sock_flow_entries**.

Unlike RPS, RFS allows both the receive queue and the application to share the same CPU when processing packet flows. This can result in improved performance in some cases. However, such improvements are dependent on factors such as cache hierarchy, application load, and the like.

getsockopt support for TCP thin-streams

Thin-stream is a term used to characterize transport protocols wherein applications send data at such a low rate that the protocol's retransmission mechanisms are not fully saturated. Applications that use thin-stream protocols typically transport via reliable protocols like TCP; in most cases, such applications provide very time-sensitive services (for example, stock trading, online gaming, control systems).

For time-sensitive services, packet loss can be devastating to service quality. To help prevent this, the **`getsockopt`** call has been enhanced to support two extra options:

`TCP_THIN_DUPACK`
: This Boolean enables dynamic triggering of retransmissions after one dupACK for thin streams.

`TCP_THIN_LINEAR_TIMEOUTS`
: This Boolean enables dynamic triggering of linear timeouts for thin streams.

Both options are specifically activated by the application. For more information about these options, refer to **`file:///usr/share/doc/kernel-doc-`*`version`*`/Documentation/networking/ip-sysctl.txt`**. For more information about thin-streams, refer to **`file:///usr/share/doc/kernel-doc-`*`version`*`/Documentation/networking/tcp-thin.txt`**.

Transparent Proxy (TProxy) support

The kernel can now handle non-locally bound IPv4 TCP and UDP sockets to support transparent proxies. To enable this, you will need to configure iptables accordingly. You will also need to enable and configure policy routing properly.

For more information about transparent proxies, refer to **`file:///usr/share/doc/kernel-doc-`*`version`*`/Documentation/networking/tproxy.txt`**.

8.2. Optimized Network Settings

Performance tuning is usually done in a pre-emptive fashion. Often, we adjust known variables before running an application or deploying a system. If the adjustment proves to be ineffective, we try adjusting other variables. The logic behind such thinking is that *by default*, the system is not operating at an optimal level of performance; as such, we *think* we need to adjust the system accordingly. In some cases, we do so via calculated guesses.

As mentioned earlier, the network stack is mostly self-optimizing. In addition, effectively tuning the network requires a thorough understanding not just of how the network stack works, but also of the specific system's network resource requirements. Incorrect network performance configuration can actually lead to degraded performance.

For example, consider the *bufferfloat problem*. Increasing buffer queue depths results in TCP connections that have congestion windows larger than the link would otherwise allow (due to deep buffering). However, those connections also have huge RTT values since the frames spend so much time in-queue. This, in turn, actually results in sub-optimal output, as it would become impossible to detect congestion.

When it comes to network performance, it is advisable to keep the default settings *unless* a particular performance issue becomes apparent. Such issues include frame loss, significantly reduced throughput, and the like. Even then, the best solution is often one that results from meticulous study of the problem,

rather than simply tuning settings upward (increasing buffer/queue lengths, reducing interrupt latency, etc).

To properly diagnose a network performance problem, use the following tools:

netstat

A command-line utility that prints network connections, routing tables, interface statistics, masquerade connections and multicast memberships. It retrieves information about the networking subsystem from the **/proc/net/** file system. These files include:

- **/proc/net/dev** (device information)
- **/proc/net/tcp** (TCP socket information)
- **/proc/net/unix** (Unix domain socket information)

For more information about **netstat** and its referenced files from **/proc/net/**, refer to the **netstat** man page: **man netstat**.

dropwatch

A monitoring utility that monitors packets dropped by the kernel. For more information, refer to the **dropwatch** man page: **man dropwatch**.

ip

A utility for managing and monitoring routes, devices, policy routing, and tunnels. For more information, refer to the **ip** man page: **man ip**.

ethtool

A utility for displaying and changing NIC settings. For more information, refer to the **ethtool** man page: **man ethtool**.

/proc/net/snmp

A file that displays ASCII data needed for the IP, ICMP, TCP, and UDP management information bases for an **snmp** agent. It also displays real-time UDP-lite statistics.

The *SystemTap Beginners Guide* contains several sample scripts you can use to profile and monitor network performance. This guide is available from http://access.redhat.com/site/documentation/Red_Hat_Enterprise_Linux/.

After collecting relevant data on a network performance problem, you should be able to formulate a theory — and, hopefully, a solution. [5] For example, an increase in UDP input errors in **/proc/net/snmp** indicates that one or more socket receive queues are full when the network stack attempts to queue new frames into an application's socket.

This indicates that packets are bottlenecked at *at least* one socket queue, which means either the socket queue drains packets too slowly, or packet volume is too large for that socket queue. If it is the latter, then verify the logs of any network-intensive application for lost data -- to resolve this, you would need to optimize or reconfigure the offending application.

Socket receive buffer size

Socket send and receive sizes are dynamically adjusted, so they rarely need to be manually edited. If further analysis, such as the analysis presented in the SystemTap network example, **sk_stream_wait_memory.stp**, suggests that the socket queue's drain rate is too slow, then you can increase the depth of the application's socket queue. To do so, increase the size of receive buffers used by sockets by configuring either of the following values:

rmem_default

A kernel parameter that controls the *default* size of receive buffers used by sockets. To configure this, run the following command:

```
sysctl -w net.core.rmem_default=N
```

Replace ***N*** with the desired buffer size, in bytes. To determine the value for this kernel parameter, view **/proc/sys/net/core/rmem_default**. Bear in mind that the value of **rmem_default** should be no greater than **rmem_max** (**/proc/sys/net/core/rmem_max**); if need be, increase the value of **rmem_max**.

SO_RCVBUF

A socket option that controls the *maximum* size of a socket's receive buffer, in bytes. For more information on **SO_RCVBUF**, refer to the man page for more details: **man 7 socket**.

To configure **SO_RCVBUF**, use the **setsockopt** utility. You can retrieve the current **SO_RCVBUF** value with **getsockopt**. For more information using both utilities, refer to the **setsockopt** man page: **man setsockopt**.

8.3. Overview of Packet Reception

To better analyze network bottlenecks and performance issues, you need to understand how packet reception works. Packet reception is important in network performance tuning because the receive path is where frames are often lost. Lost frames in the receive path can cause a significant penalty to network performance.

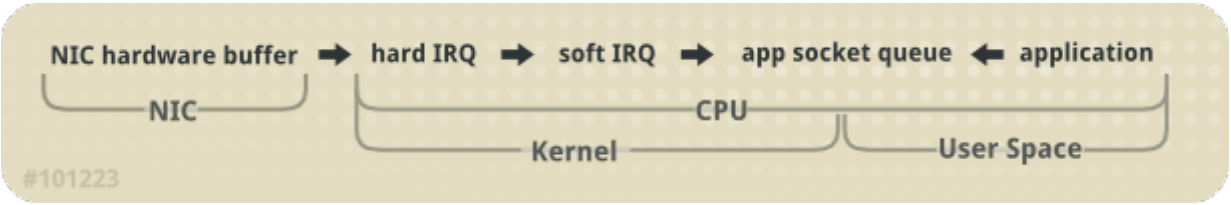


Figure 8.1. Network receive path diagram

The Linux kernel receives each frame and subjects it to a four-step process:

1. *Hardware Reception*: the *network interface card* (NIC) receives the frame on the wire. Depending on its driver configuration, the NIC transfers the frame either to an internal hardware buffer memory or to a specified ring buffer.
2. *Hard IRQ*: the NIC asserts the presence of a net frame by interrupting the CPU. This causes the NIC driver to acknowledge the interrupt and schedule the *soft IRQ operation*.
3. *Soft IRQ*: this stage implements the actual frame-receiving process, and is run in **softirq** context. This means that the stage pre-empts all applications running on the specified CPU, but

still allows hard IRQs to be asserted.

In this context (running on the same CPU as hard IRQ, thereby minimizing locking overhead), the kernel actually removes the frame from the NIC hardware buffers and processes it through the network stack. From there, the frame is either forwarded, discarded, or passed to a target listening socket.

When passed to a socket, the frame is appended to the application that owns the socket. This process is done iteratively until the NIC hardware buffer runs out of frames, or until the *device weight* (**dev_weight**). For more information about device weight, refer to Section 8.4.1, “NIC Hardware Buffer”

4. *Application receive*: the application receives the frame and dequeues it from any owned sockets via the standard POSIX calls (**read**, **recv**, **recvfrom**). At this point, data received over the network no longer exists on the network stack.

CPU/cache affinity

To maintain high throughput on the receive path, it is recommended that you keep the L2 cache *hot*. As described earlier, network buffers are received on the same CPU as the IRQ that signaled their presence. This means that buffer data will be on the L2 cache of that receiving CPU.

To take advantage of this, place process affinity on applications expected to receive the most data on the NIC that shares the same core as the L2 cache. This will maximize the chances of a cache hit, and thereby improve performance.

8.4. Resolving Common Queuing/Frame Loss Issues

By far, the most common reason for frame loss is a *queue overrun*. The kernel sets a limit to the length of a queue, and in some cases the queue fills faster than it drains. When this occurs for too long, frames start to get dropped.

As illustrated in Figure 8.1, “Network receive path diagram”, there are two major queues in the receive path: the NIC hardware buffer and the socket queue. Both queues need to be configured accordingly to protect against queue overruns.

8.4.1. NIC Hardware Buffer

The NIC fills its hardware buffer with frames; the buffer is then drained by the **softirq**, which the NIC asserts via an interrupt. To interrogate the status of this queue, use the following command:

```
ethtool -S ethX
```

Replace ***ethX*** with the NIC's corresponding device name. This will display how many frames have been dropped within ***ethX***. Often, a drop occurs because the queue runs out of buffer space in which to store frames.

There are different ways to address this problem, namely:

Input traffic

You can help prevent queue overruns by slowing down input traffic. This can be achieved by filtering, reducing the number of joined multicast groups, lowering broadcast traffic, and the like.

Queue length

Alternatively, you can also increase the queue length. This involves increasing the number of buffers in a specified queue to whatever maximum the driver will allow. To do so, edit the **rx**/**tx**

ring parameters of ***ethX*** using:

```
ethtool --set-ring ethX
```

Append the appropriate **rx** or **tx** values to the aforementioned command. For more information, refer to **man ethtool**.

Device weight

You can also increase the rate at which a queue is drained. To do this, adjust the NIC's *device weight* accordingly. This attribute refers to the maximum number of frames that the NIC can receive before the **softirq** context has to yield the CPU and reschedule itself. It is controlled by the **/proc/sys/net/core/dev_weight** variable.

Most administrators have a tendency to choose the third option. However, keep in mind that there are consequences for doing so. Increasing the number of frames that can be received from a NIC in one iteration implies extra CPU cycles, during which no applications can be scheduled on that CPU.

8.4.2. Socket Queue

Like the NIC hardware queue, the socket queue is filled by the network stack from the **softirq** context. Applications then drain the queues of their corresponding sockets via calls to **read**, **recvfrom**, and the like.

To monitor the status of this queue, use the **netstat** utility; the **Recv-Q** column displays the queue size. Generally speaking, overruns in the socket queue are managed in the same way as NIC hardware buffer overruns (i.e. Section 8.4.1, “NIC Hardware Buffer”):

Input traffic

The first option is to slow down input traffic by configuring the rate at which the queue fills. To do so, either filter frames or pre-emptively drop them. You can also slow down input traffic by lowering the NIC's device weight [6].

Queue depth

You can also avoid socket queue overruns by increasing the queue depth. To do so, increase the value of either the **rmem_default** kernel parameter or the **SO_RCVBUF** socket option. For more information on both, refer to Section 8.2, “Optimized Network Settings”.

Application call frequency

Whenever possible, optimize the application to perform calls more frequently. This involves modifying or reconfiguring the network application to perform more frequent POSIX calls (such as **recv**, **read**). In turn, this allows an application to drain the queue faster.

For many administrators, increasing the queue depth is the preferable solution. This is the easiest solution, but it may not always work long-term. As networking technologies get faster, socket queues will continue to fill more quickly. Over time, this means having to re-adjust the queue depth accordingly.

The best solution is to enhance or configure the application to drain data from the kernel more quickly, even if it means queuing the data in application space. This lets the data be stored more flexibly, since it can be swapped out and paged back in as needed.

8.5. Multicast Considerations

When multiple applications listen to a multicast group, the kernel code that handles multicast frames is required by design to duplicate network data for each individual socket. This duplication is time-consuming and occurs in the **softirq** context.

Adding multiple listeners on a single multicast group therefore has a direct impact on the **softirq** context's execution time. Adding a listener to a multicast group implies that the kernel must create an additional copy for each frame received for that group.

The effect of this is minimal at low traffic volume and small listener numbers. However, when multiple sockets listen to a high-traffic multicast group, the increased execution time of the **softirq** context can lead to frame drops at both the network card and the socket queue. Increased **softirq** runtimes translate to reduced opportunity for applications to run on heavily-loaded systems, so the rate at which multicast frames are lost increases as the number of applications listening to a high-volume multicast group increases.

Resolve this frame loss by optimizing your socket queues and NIC hardware buffers, as described in Section 8.4.2, “Socket Queue” or Section 8.4.1, “NIC Hardware Buffer”. Alternatively, you can optimize an application's socket use; to do so, configure the application to control a single socket and disseminate the received network data quickly to other user-space processes.

8.6. Receive-Side Scaling (RSS)

Receive-Side Scaling (RSS), also known as multi-queue receive, distributes network receive processing across several hardware-based receive queues, allowing inbound network traffic to be processed by multiple CPUs. RSS can be used to relieve bottlenecks in receive interrupt processing caused by overloading a single CPU, and to reduce network latency.

To determine whether your network interface card supports RSS, check whether multiple interrupt request queues are associated with the interface in **/proc/interrupts**. For example, if you are interested in the **p1p1** interface:

```
# egrep 'CPU|p1p1' /proc/interrupts
      CPU0    CPU1    CPU2    CPU3    CPU4    CPU5
89:   40187       0       0       0       0       0   IR-PCI-MSI-edge   p1p1-0
90:       0     790       0       0       0       0   IR-PCI-MSI-edge   p1p1-1
91:       0       0     959       0       0       0   IR-PCI-MSI-edge   p1p1-2
92:       0       0       0    3310       0       0   IR-PCI-MSI-edge   p1p1-3
93:       0       0       0       0     622       0   IR-PCI-MSI-edge   p1p1-4
94:       0       0       0       0       0    2475   IR-PCI-MSI-edge   p1p1-5
```

The preceding output shows that the NIC driver created 6 receive queues for the **p1p1** interface (**p1p1-0** through **p1p1-5**). It also shows how many interrupts were processed by each queue, and which CPU serviced the interrupt. In this case, there are 6 queues because by default, this particular NIC driver creates one queue per CPU, and this system has 6 CPUs. This is a fairly common pattern amongst NIC drivers.

Alternatively, you can check the output of **ls -1 /sys/devices/*/*/*device_pci_address*/msi_irqs** after the network driver is loaded. For example, if you are interested in a device with a PCI address of **0000:01:00.0**, you can list the interrupt request queues of that device with the following command:

```
# ls -1 /sys/devices/*/*/0000:01:00.0/msi_irqs
101
102
103
104
105
106
107
108
109
```

RSS is enabled by default. The number of queues (or the CPUs that should process network activity) for RSS are configured in the appropriate network device driver. For the **bnx2x** driver, it is configured in ***num_queues***. For the **sfc** driver, it is configured in the ***rss_cpus*** parameter. Regardless, it is typically configured in **/sys/class/net/*device*/queues/*rx-queue*/**, where ***device*** is the name of the network device (such as **eth1**) and ***rx-queue*** is the name of the appropriate receive queue.

When configuring RSS, Red Hat recommends limiting the number of queues to one per physical CPU core. Hyper-threads are often represented as separate cores in analysis tools, but configuring queues for all cores including logical cores such as hyper-threads has not proven beneficial to network performance.

When enabled, RSS distributes network processing equally between available CPUs based on the amount of processing each CPU has queued. However, you can use the **ethtool *--show-rxfh-indir*** and ***--set-rxfh-indir*** parameters to modify how network activity is distributed, and weight certain types of network activity as more important than others.

The **irqbalance** daemon can be used in conjunction with RSS to reduce the likelihood of cross-node memory transfers and cache line bouncing. This lowers the latency of processing network packets. If both **irqbalance** and RSS are in use, lowest latency is achieved by ensuring that **irqbalance** directs interrupts associated with a network device to the appropriate RSS queue.

8.7. Receive Packet Steering (RPS)

Receive Packet Steering (RPS) is similar to RSS in that it is used to direct packets to specific CPUs for processing. However, RPS is implemented at the software level, and helps to prevent the hardware queue of a single network interface card from becoming a bottleneck in network traffic.

RPS has several advantages over hardware-based RSS:

- RPS can be used with any network interface card.
- It is easy to add software filters to RPS to deal with new protocols.
- RPS does not increase the hardware interrupt rate of the network device. However, it does introduce inter-processor interrupts.

RPS is configured per network device and receive queue, in the **/sys/class/net/*device*/queues/*rx-queue*/rps_cpus** file, where ***device*** is the name of the network device (such as **eth0**) and ***rx-queue*** is the name of the appropriate receive queue (such as **rx-0**).

The default value of the **rps_cpus** file is zero. This disables RPS, so the CPU that handles the network interrupt also processes the packet.

To enable RPS, configure the appropriate **rps_cpus** file with the CPUs that should process packets

from the specified network device and receive queue.

The **rps_cpus** files use comma-delimited CPU bitmaps. Therefore, to allow a CPU to handle interrupts for the receive queue on an interface, set the value of their positions in the bitmap to 1. For example, to handle interrupts with CPUs 0, 1, 2, and 3, set the value of **rps_cpus** to **00001111** (1+2+4+8), or **f** (the hexadecimal value for 15).

For network devices with single transmit queues, best performance can be achieved by configuring RPS to use CPUs in the same memory domain. On non-NUMA systems, this means that all available CPUs can be used. If the network interrupt rate is extremely high, excluding the CPU that handles network interrupts may also improve performance.

For network devices with multiple queues, there is typically no benefit to configuring both RPS and RSS, as RSS is configured to map a CPU to each receive queue by default. However, RPS may still be beneficial if there are fewer hardware queues than CPUs, and RPS is configured to use CPUs in the same memory domain.

8.8. Receive Flow Steering (RFS)

Receive Flow Steering (RFS) extends RPS behavior to increase the CPU cache hit rate and thereby reduce network latency. Where RPS forwards packets based solely on queue length, RFS uses the RPS backend to calculate the most appropriate CPU, then forwards packets based on the location of the application consuming the packet. This increases CPU cache efficiency.

RFS is disabled by default. To enable RFS, you must edit two files:

/proc/sys/net/core/rps_sock_flow_entries

Set the value of this file to the maximum expected number of concurrently active connections. We recommend a value of **32768** for moderate server loads. All values entered are rounded up to the nearest power of 2 in practice.

/sys/class/net/*device*/queues/*rx-queue*/rps_flow_cnt

Replace ***device*** with the name of the network device you wish to configure (for example, **eth0**), and ***rx-queue*** with the receive queue you wish to configure (for example, **rx-0**).

Set the value of this file to the value of **rps_sock_flow_entries** divided by **N**, where **N** is the number of receive queues on a device. For example, if **rps_flow_entries** is set to **32768** and there are 16 configured receive queues, **rps_flow_cnt** should be set to **2048**. For single-queue devices, the value of **rps_flow_cnt** is the same as the value of **rps_sock_flow_entries**.

Data received from a single sender is not sent to more than one CPU. If the amount of data received from a single sender is greater than a single CPU can handle, configure a larger frame size to reduce the number of interrupts and therefore the amount of processing work for the CPU. Alternatively, consider NIC offload options or faster CPUs.

Consider using **numactl** or **taskset** in conjunction with RFS to pin applications to specific cores, sockets, or NUMA nodes. This can help prevent packets from being processed out of order.

8.9. Accelerated RFS

Accelerated RFS boosts the speed of RFS by adding hardware assistance. Like RFS, packets are forwarded based on the location of the application consuming the packet. Unlike traditional RFS, however, packets are sent directly to a CPU that is local to the thread consuming the data: either the CPU that is executing the application, or a CPU local to that CPU in the cache hierarchy.

Accelerated RFS is only available if the following conditions are met:

- Accelerated RFS must be supported by the network interface card. Accelerated RFS is supported by cards that export the **`ndo_rx_flow_steer()`** netdevice function.
- **`ntuple`** filtering must be enabled.

Once these conditions are met, CPU to queue mapping is deduced automatically based on traditional RFS configuration. That is, CPU to queue mapping is deduced based on the IRQ affinities configured by the driver for each receive queue. Refer to Section 8.8, “Receive Flow Steering (RFS)” for details on configuring traditional RFS.

Red Hat recommends using accelerated RFS wherever using RFS is appropriate and the network interface card supports hardware acceleration.

[4] Ensuring cache affinity between a CPU and a NIC means configuring them to share the same L2 cache. For more information, refer to Section 8.3, “Overview of Packet Reception”.

[5] Section 8.3, “Overview of Packet Reception” contains an overview of packet travel, which should help you locate and map bottleneck-prone areas in the network stack.

[6] Device weight is controlled via **`/proc/sys/net/core/dev_weight`**. For more information about device weight and the implications of adjusting it, refer to Section 8.4.1, “NIC Hardware Buffer”.

Revision History

Revision 4.0-43.404 **Mon Nov 25 2013** **Rüdiger Landmann**

Rebuild with Publican 4.0.0

Revision 4.0-43 **Wed Nov 13 2013** **Laura Bailey**

Building for Red Hat Enterprise Linux 6.5 GA.

Revision 4.0-42 **Tue Oct 15 2013** **Laura Bailey**

Minor corrections for RHEL 6.5 based on customer feedback (BZ#1011676).

Revision 4.0-41 **Thu Sep 12 2013** **Laura Bailey**

Minor corrections for RHEL 6.5 based on SME feedback.
Minor corrections for RHEL 6.5 based on QE feedback.

Revision 4.0-38 **Tue Aug 13 2013** **Laura Bailey**

Noted customer-facing changes in perf between RHEL 6.4 and 6.5.
Final corrections to RSS, RPS, RFS, and accelerated RFS sections based on SME feedback.
Final corrections to KSM notes based on SME feedback.

Revision 4.0-35 **Fri Aug 09 2013** **Laura Bailey**

Applied SME feedback.
Noted performance improvements to KSM (BZ#977627).
Corrected numa man page reference (BZ#988240).
Noted updates to **hdparm** (BZ#978096).

Revision 4.0-32 **Tue Aug 06 2013** **Laura Bailey**

Noted updates to ext3 multi-threaded write performance (BZ#978099).
Noted new System z hardware counters available to perf (BZ#977626).
Noted improvements to copy from/to user functions (BZ#977608).
Added Section 4.1.3, “Hardware performance policy (**x86_energy_perf_policy**)” and notes on cpupowerutils (BZ#853280).
Noted turbostat man page.

Revision 4.0-30 **Tue Aug 06 2013** **Laura Bailey**

Corrected section on Accelerated RFS (BZ#976108).
Ensured that screen code examples did not overflow boundaries.

Revision 4.0-28 **Mon Aug 05 2013** **Laura Bailey**

Noted improvements to throughput from CIFS update (BZ#973504).
Added notes on Orlov algorithm use in GFS2 (BZ#973506).
Confirmed tuned profile descriptions (BZ#986147).
Noted change in default value of kernel.sched_migration_cost (BZ#986149).
Noted changes to the throughput-performance and latency-performance profiles (BZ#986786).

Revision 4.0-26 **Wed Jul 31 2013** **Laura Bailey**

Added section on Intel's turbostat tool (BZ#970396).

Revision 4.0-25 **Fri Jul 26 2013** **Laura Bailey**

Corrected sections on Receive-Side Scaling, Receive Packet Steering, and Receive Flow Steering

(BZ#976108).
Added section on Accelerated RFS (BZ#976108).

Revision 4.0-24 Thu Jul 25 2013 Laura Bailey

Added sections on Receive-Side Scaling, Receive Packet Steering, and Receive Flow Steering (BZ#976108).

Revision 4.0-23 Mon Jul 01 2013 Laura Bailey

Users can now use multiple IOMMU pools (BZ#977628).

Revision 4.0-22 Tue Jun 25 2013 Laura Bailey

Corrected missing sentence (BZ#964003).

Revision 4.0-21 Tue May 28 2013 Laura Bailey

Updated XFS section to provide clearer recommendations about directory block sizes.

Revision 4.0-20 Wed Jan 16 2013 Laura Bailey

Minor corrections for consistency (BZ#868404).

Revision 4.0-18 Tue Nov 27 2012 Laura Bailey

Publishing for Red Hat Enterprise Linux 6.4 Beta.

Revision 4.0-17 Mon Nov 19 2012 Laura Bailey

Added SME feedback re. numad section (BZ#868404).

Revision 4.0-16 Thu Nov 08 2012 Laura Bailey

Added draft section on numad (BZ#868404).

Revision 4.0-15 Wed Oct 17 2012 Laura Bailey

Applying SME feedback to block discard discussion and moved section to under Mount Options (BZ#852990).
Updated performance profile descriptions (BZ#858220).

Revision 4.0-13 Wed Oct 17 2012 Laura Bailey

Updated performance profile descriptions (BZ#858220).

Revision 4.0-12 Tue Oct 16 2012 Laura Bailey

Improved book navigation (BZ#854082).
Corrected the definition of ***file-max*** (BZ#854094).
Corrected the definition of ***threads-max*** (BZ#856861).

Revision 4.0-9 Tue Oct 9 2012 Laura Bailey

Added FSTRIM recommendation to the File Systems chapter (BZ#852990).
Updated description of the ***threads-max*** parameter according to customer feedback (BZ#856861).
Updated note about GFS2 fragmentation management improvements BZ#857782).

Revision 4.0-6 Thu Oct 4 2012 Laura Bailey

Added new section on numastat utility (BZ#853274).

Revision 4.0-3 **Tue Sep 18 2012** **Laura Bailey**

Added note re. new perf capabilities (BZ#854082).
Corrected the description of the file-max parameter (BZ#854094).

Revision 4.0-2 **Mon Sep 10 2012** **Laura Bailey**

Added BTRFS section and basic introduction to the file system (BZ#852978).
Noted Valgrind integration with GDB (BZ#853279).

Revision 3.0-15 **Thursday March 22 2012** **Laura Bailey**

Added and updated descriptions of tuned-adm profiles (BZ#803552).

Revision 3.0-10 **Friday March 02 2012** **Laura Bailey**

Updated the threads-max and file-max parameter descriptions (BZ#752825).
Updated slice_idle parameter default value (BZ#785054).

Revision 3.0-8 **Thursday February 02 2012** **Laura Bailey**

Restructured and added details about taskset and binding CPU and memory allocation with numactl to Section 4.1.2, “Tuning CPU Performance” (BZ#639784).
Corrected use of internal links (BZ#786099).

Revision 3.0-5 **Tuesday January 17 2012** **Laura Bailey**

Minor corrections to Section 5.3, “Using Valgrind to Profile Memory Usage” (BZ#639793).

Revision 3.0-3 **Wednesday January 11 2012** **Laura Bailey**

Ensured consistency among internal and external hyperlinks (BZ#752796).
Added Section 5.3, “Using Valgrind to Profile Memory Usage” (BZ#639793).
Added Section 4.1.2, “Tuning CPU Performance” and restructured Chapter 4, *CPU* (BZ#639784).

Revision 1.0-0 **Friday December 02 2011** **Laura Bailey**

Release for GA of Red Hat Enterprise Linux 6.2.